

# Summary of LHC results from LHCP2015 (and outlook)

*Paris Sphicas  
CERN & University of Athens  
Wine and Cheese Seminar  
Fermilab, Oct 2, 2015*

- **Our old-time friend: the Standard Model**
  - ◆ The Higgs; EWK model, and its obese member at the top
  - ◆ Heavy Flavors: living for  $\sim 10^{-12}$  s
  - ◆ QCD with nearly-free partons.
- **Our resilient adversary: the Standard Model**
  - ◆ No SUSY (yet)
  - ◆ No light from Dark Matter (yet)
  - ◆ No new resonances (yet), etc...
- **What next**

**This talk was originally given as  
“Experimental Summary” at LHCP2015**

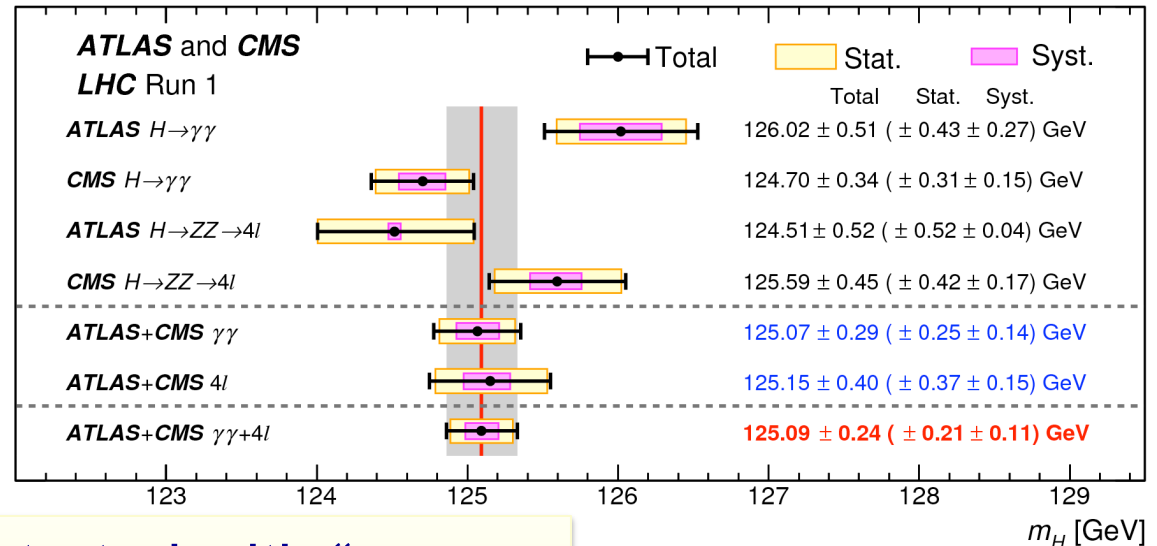
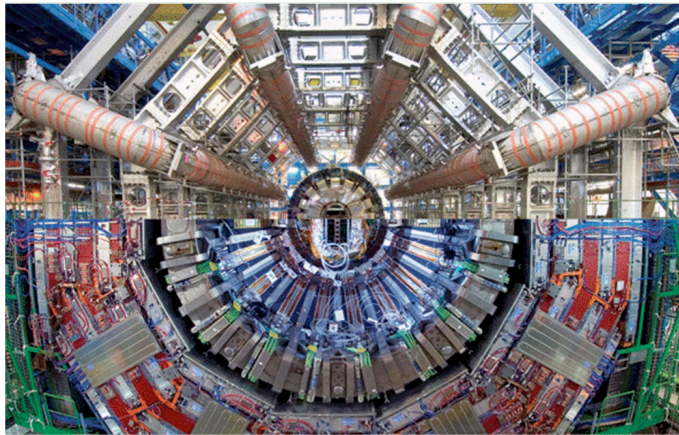
***Thankfully, no-one really expected a real  
summary...***

**→ *not a summary;*  
instead, very tight cuts have been applied  
→ experiment highlights,  
some summaries, some observations,  
some opinions,  
some calls for help**



# The BEH scalar (aka “Higgs boson”)

- **Sqrt(2) = 1.41. Useful when dividing errors.**

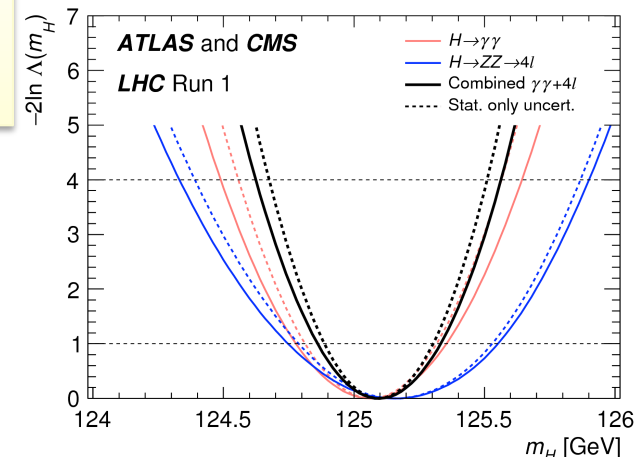


90's, 00's, 10,11: talks started with “... we know everything ... except its mass...”

$$M_H = 125.09 \pm 0.24 \text{ GeV}$$

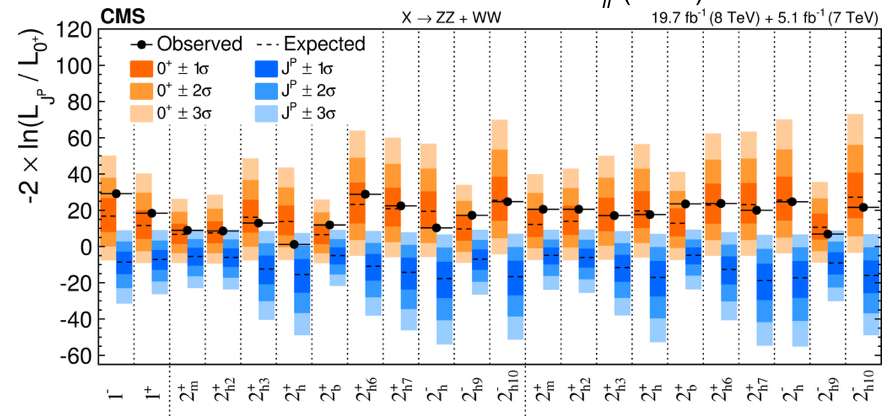
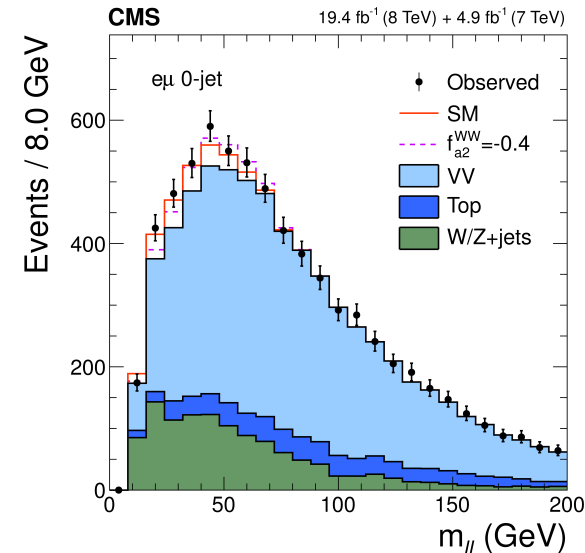
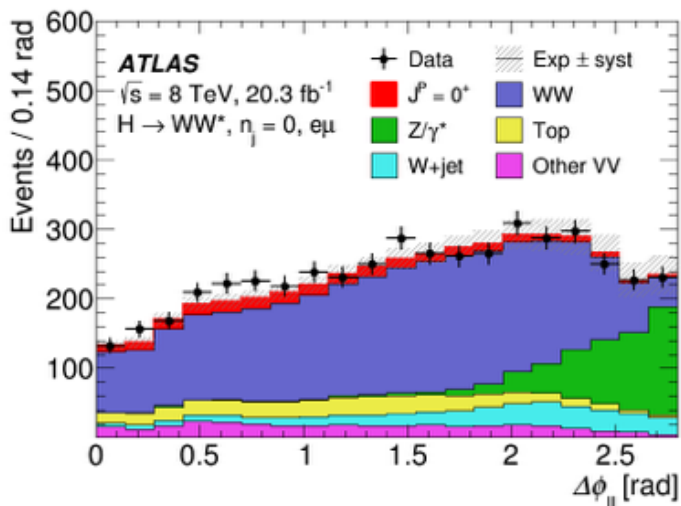
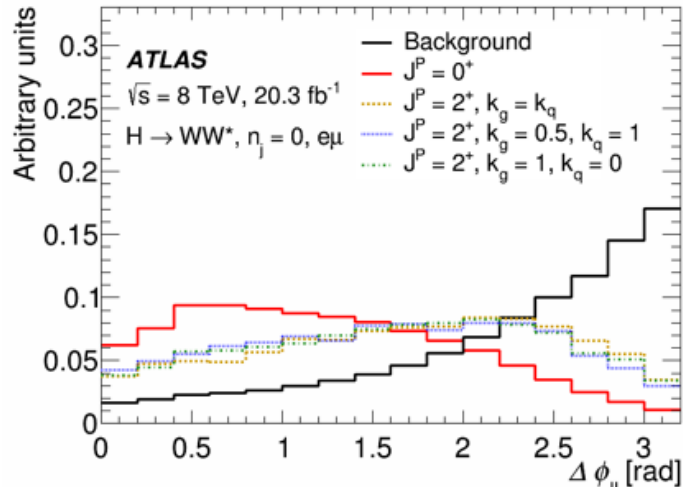
$$= \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV}$$

$$\delta m_H / m_H = 0.2\%$$



# A scalar, beyond “reasonable” doubts

## ■ $\gamma\gamma$ , WW, ZZ modes



Alternatives tested:  $0^\pm$ ,  $1^\pm$  and  $2^\pm$ ;  
 Excluded at  $>99\%$  CL

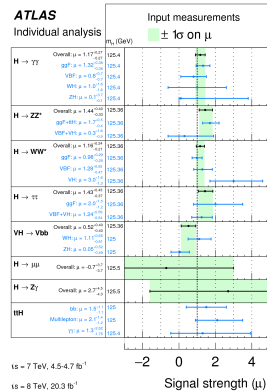
# Couplings: the combination...

## ■ Sqrt(2) = 1.41. (Constant)

ATLAS

Mass: [Phys. Rev. Lett. 114, 191803](#)

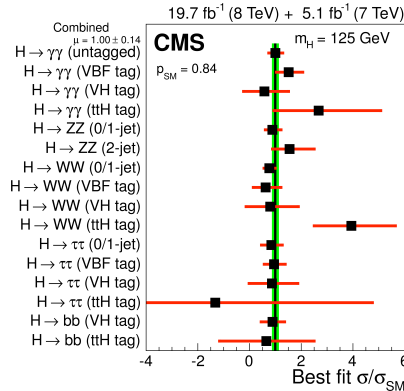
Couplings: [arXiv:1507.04548](#)



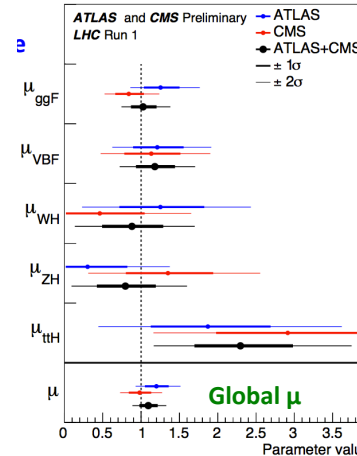
CMS

Mass and couplings:

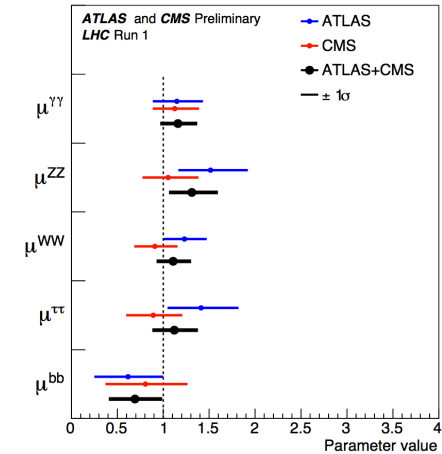
[Eur. Phys. J. C 75 \(2015\) 212](#)



SM BRs assumed



SM production σ assumed



$$\mu = 1.09^{+0.11}_{-0.10}$$

Bonus: definitive observation of VBF,  $\tau\tau$

Production process	Observed Significance( $\sigma$ )	Expected Significance ( $\sigma$ )
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H → $\tau\tau$	5.5	5.0
H → bb	2.6	3.7

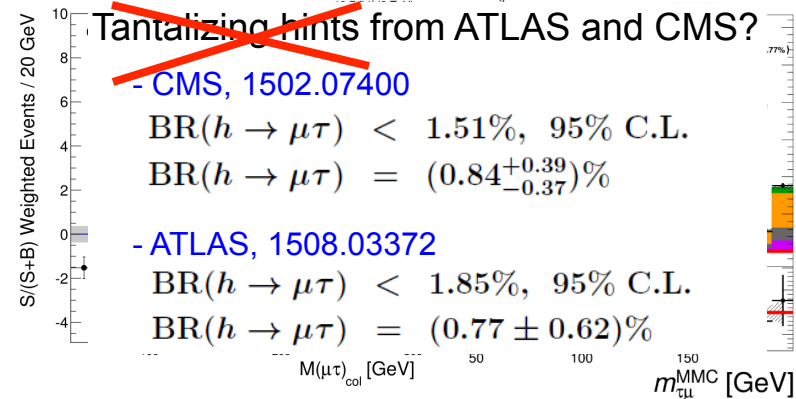
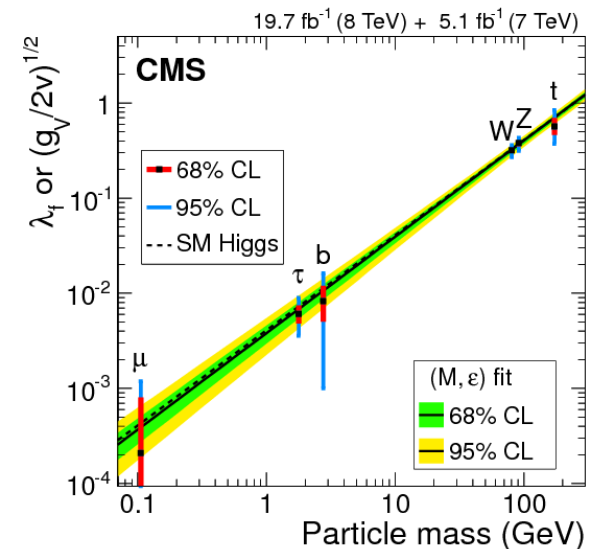
“Different parameterizations have been studied and all results are consistent the SM predictions...”

*M. Pieri*

→ The SM Higgs boson

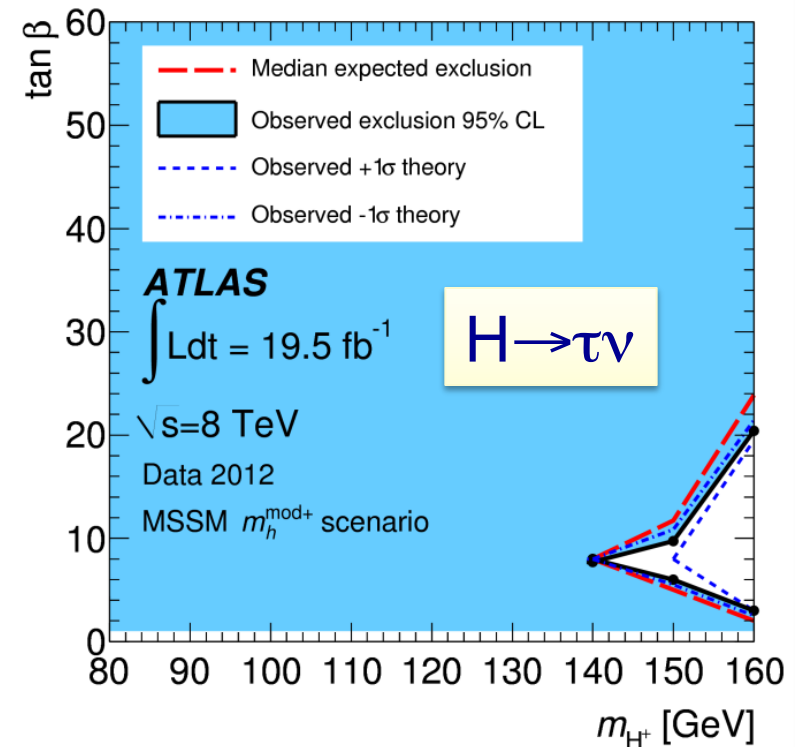
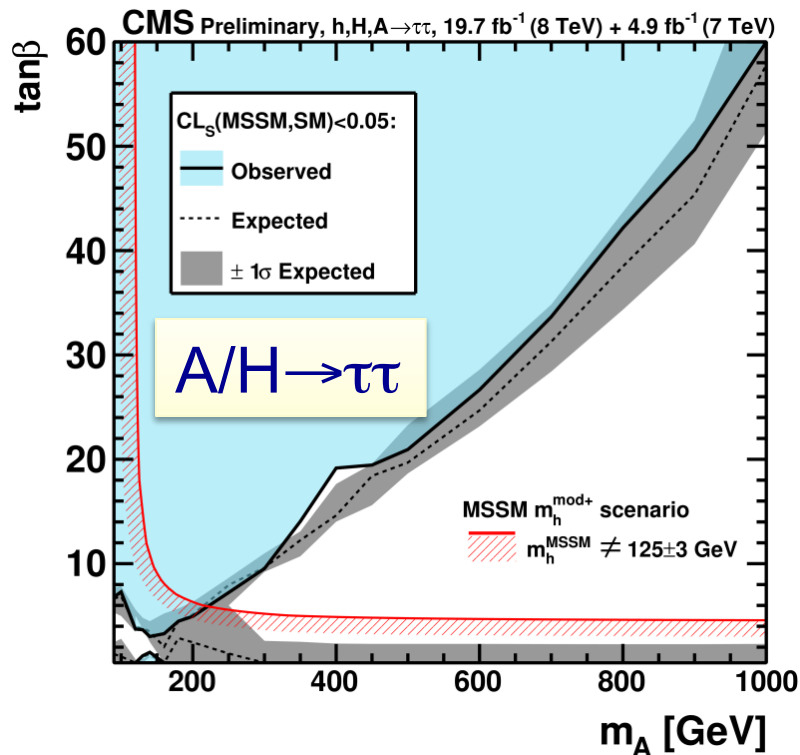
# The Standard Model Higgs boson...

- It “dances” like a Higgs (boringly, no turns, looks the same in a mirror), it mingles like a Higgs (couples to mass, and in the right proportion as in the SM...)
  - ◆ It *is* “the SM Higgs boson”.
- Perhaps there is additional behavior; or there are departures in behavior – e.g. it is a Dark Matter portal; or it violates flavor (by a little), or ...
  - ◆ But those would now go under “changes to the SM” not under the label “not the SM Higgs boson”...
    - e.g. like the top quark.



# And no extras (in the scalar sector)

- Compositeness, extra singlet, 2HDM, LFV, searches for heavy H... No signs thus far

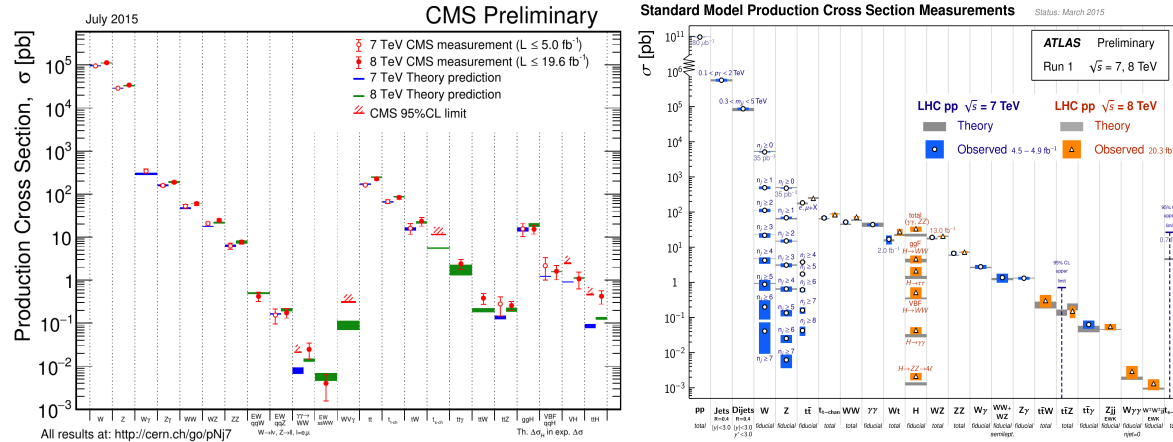


**Our old-time friend:  
the Standard Model**

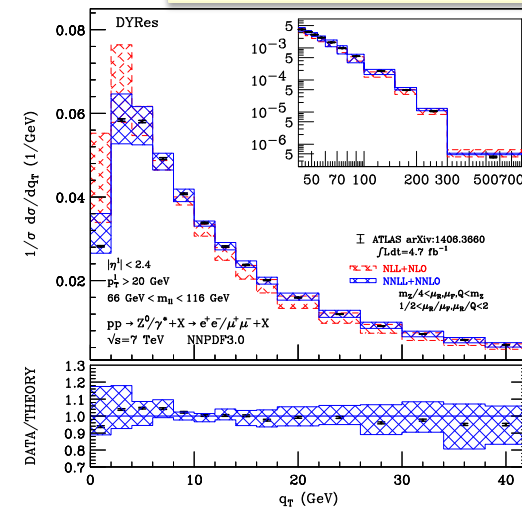
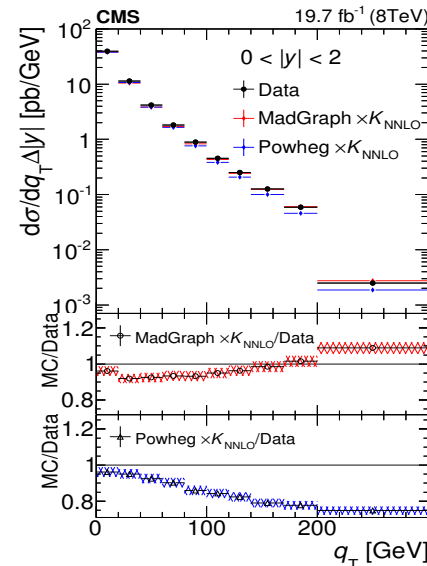
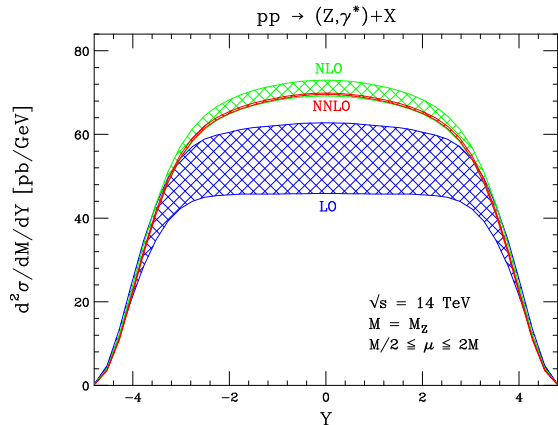
**Famous friend: EWK theory.  
With its obese member at the top.**

# EWK physics

## Understatement #1: beautiful EWK/QCD measurements



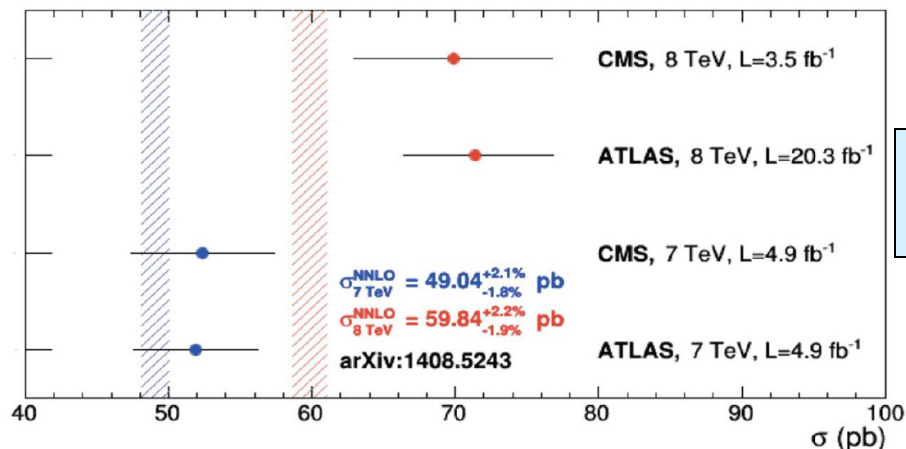
## Understatement #2: great theoretical strides; still, we want/need more:





# WW: new physics? Nope.

## ■ Started with a $2\sigma$ discrepancy in WW cross section



Was seen in ATLAS and CMS  
→ quite a bit of excitement...

Significant amount of literature  
(and some literature) on New  
Physics scenarios.

Some words of caution on  
(N)NLO, jet vetoes, etc.

CMS: full 8 TeV dataset+improvements

- H WW → included in bkg. (8%)
- NNLO calculations (7% higher)
- WW  $P_T$  resummation reweighting
- Madgraph (LO) → Powheg (NLO)

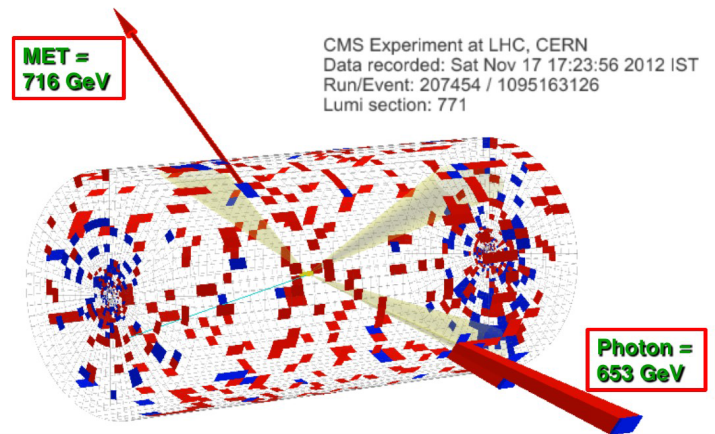
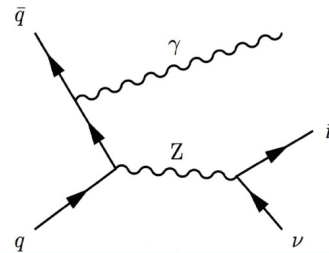
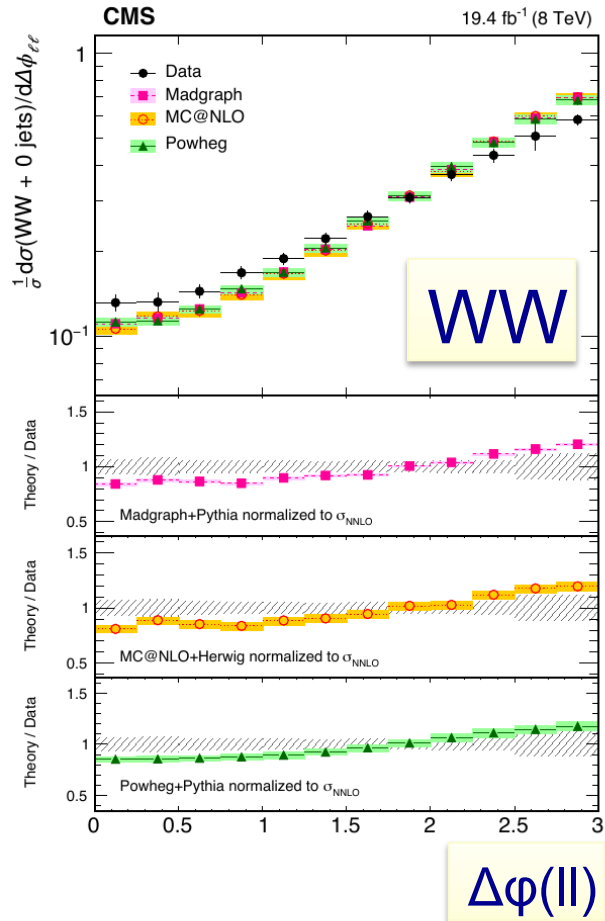
Measurement with 0-jet, 1-jet,  
same flavor, opposite-flavor events

$$\sigma^{\text{data}} = 60.1 \pm 4.8 \text{ pb}$$
$$\sigma^{\text{NNLO}} = 59.8^{+1.3}_{-1.1} \text{ pb}$$

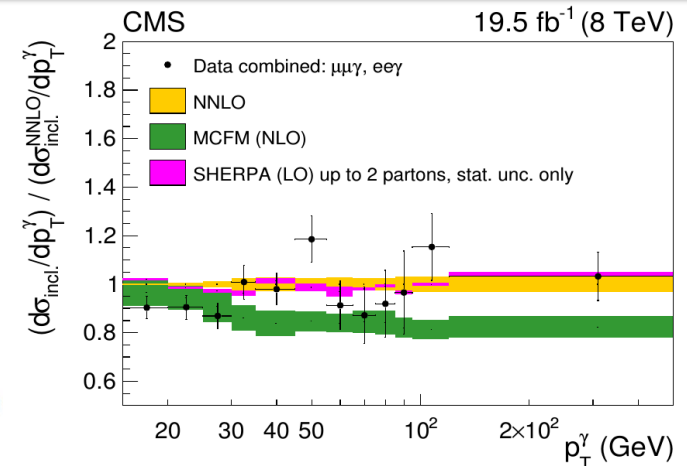
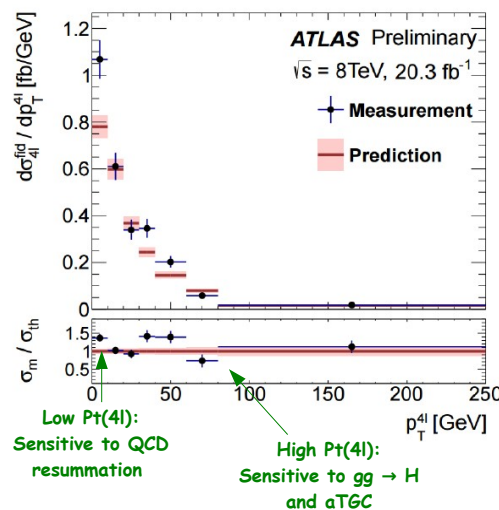


# Dibosons

## Some very nice measurements



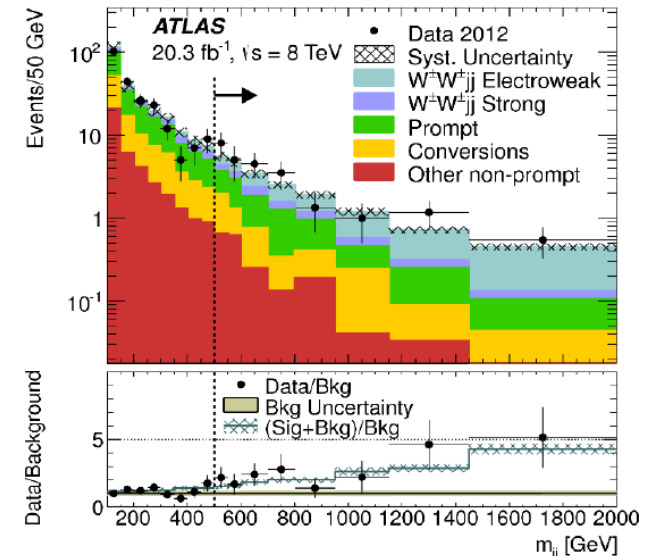
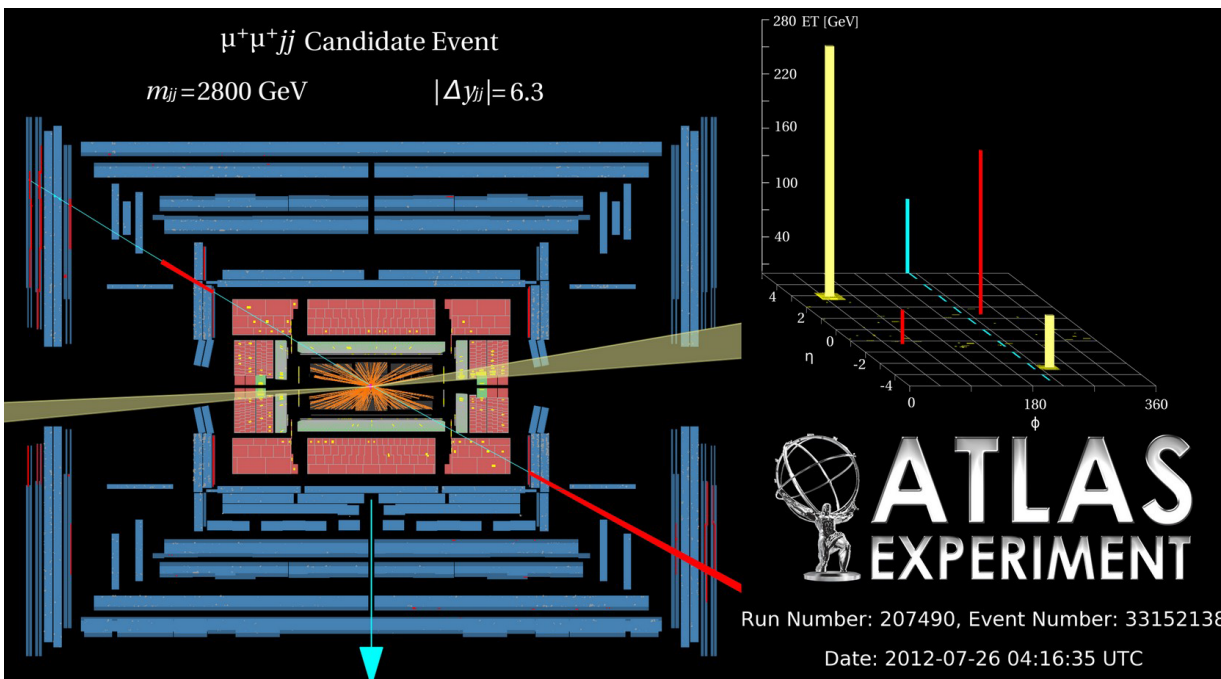
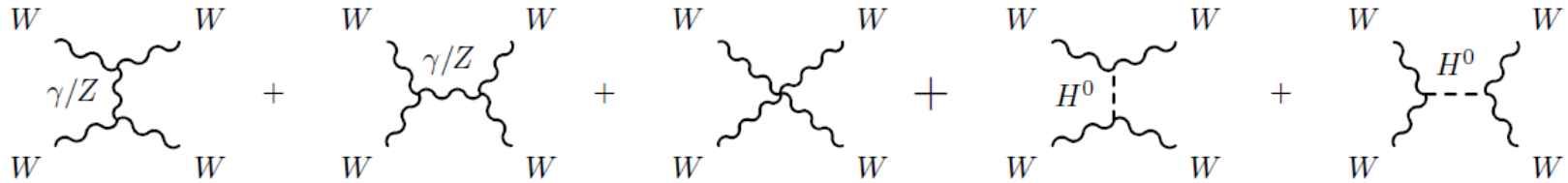
**And NLO won't do any more**



# But the real interesting one is...

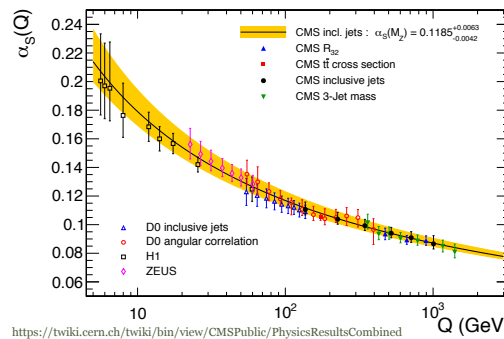
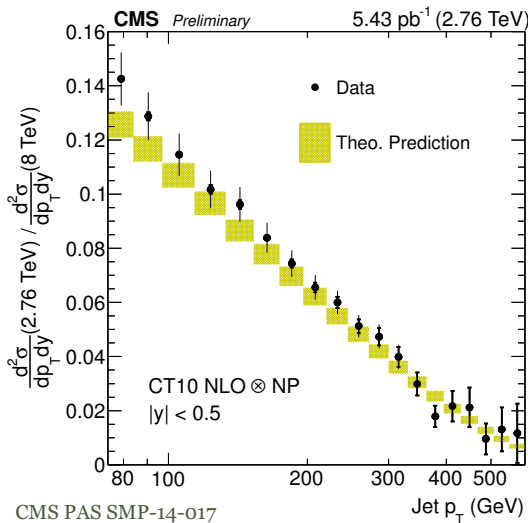
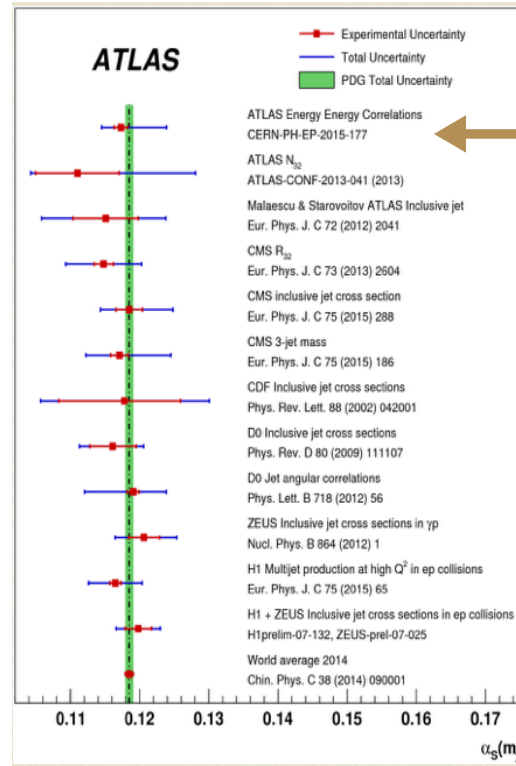
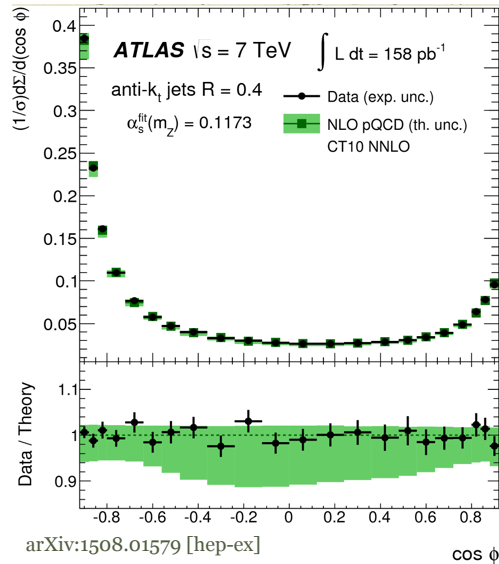
## EWK production of WW; VBS scattering

◆ Recall: one of the “raison d’être” for the Higgs



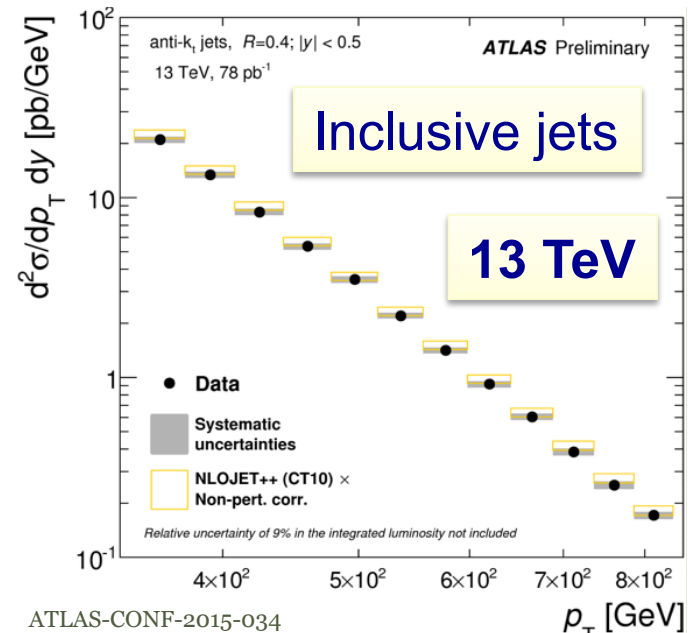
**ATLAS  $3.6\sigma$  (exp:  $2.8\sigma$ )**  
**CMS  $1.9\sigma$  (exp:  $2.9\sigma$ )**

# Perturbative QCD & Jet physics: flourishing...

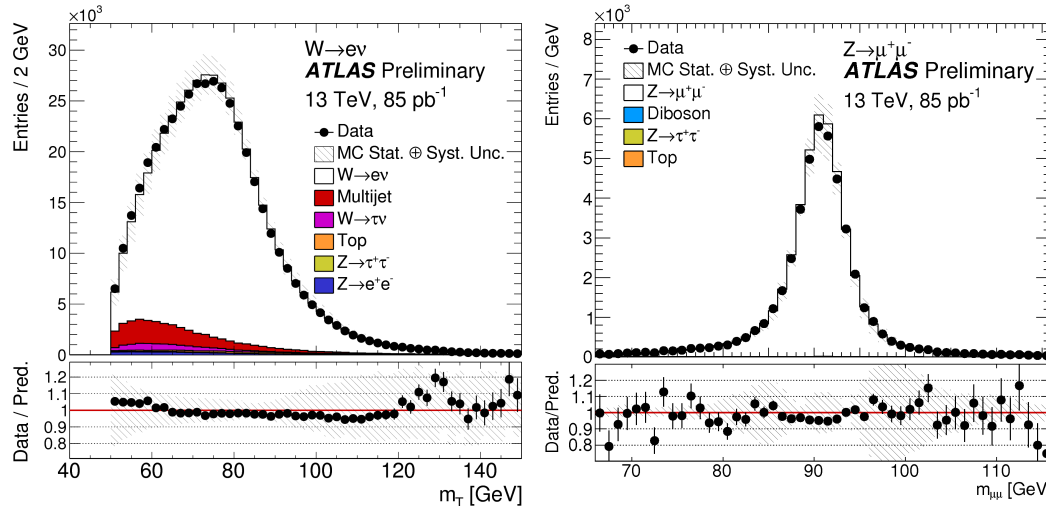


Measurement dominated by theory uncertainties

Need NNLO calculations to improve precision of  $\alpha_s$  at hadron colliders

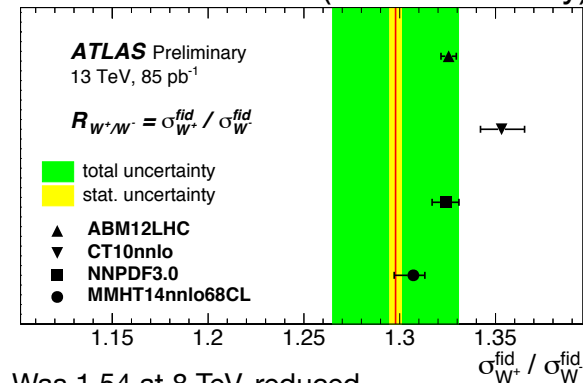


# Early 13 TeV W/Z measurements

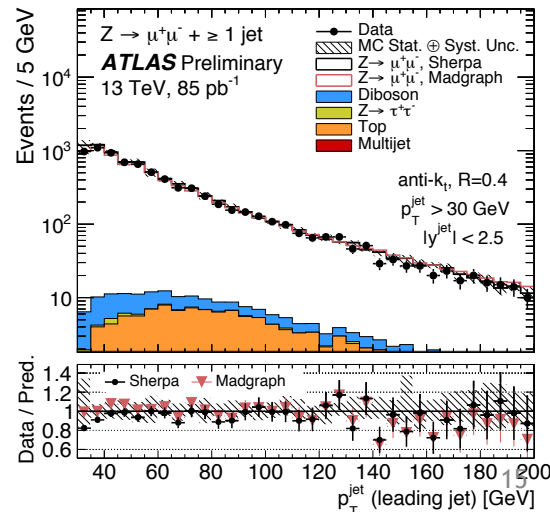
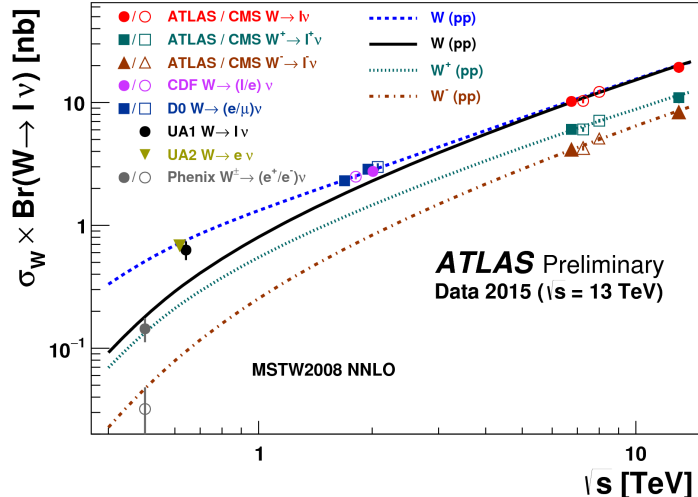


Channel	value $\pm$ stat $\pm$ syst $\pm$ lumi [pb]
$W^-$	$3344 \pm 6 \pm 113 \pm 301$
$W^+$	$4340 \pm 7 \pm 138 \pm 391$
$W^\pm$	$7684 \pm 9 \pm 232 \pm 692$
$Z$	$746 \pm 3 \pm 13 \pm 67$

W+/W- Fiducial Ratio (2.5% accuracy)



Was 1.54 at 8 TeV, reduced  
valence quark asymmetry at 13 TeV



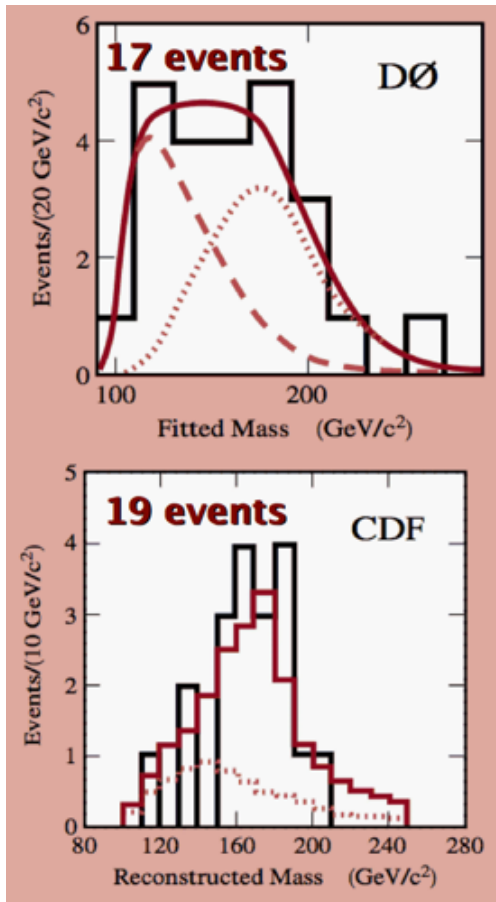
So nice to  
see these...

**The t**

# Tevatron legacy

## ■ Tevatron: twenty (...!) years of top physics

$$199_{-21}^{+19}(\text{stat}) \pm 22(\text{syst})$$



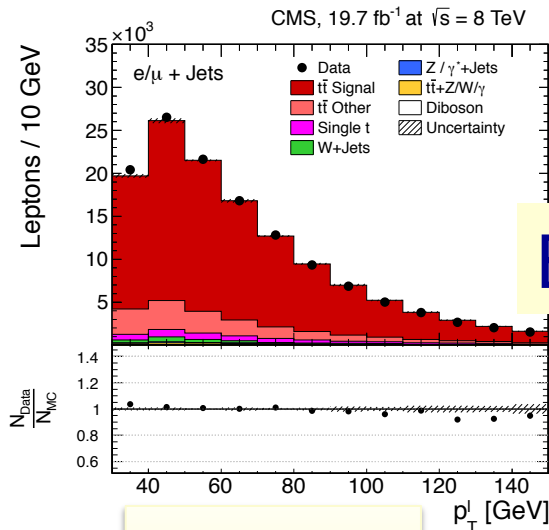
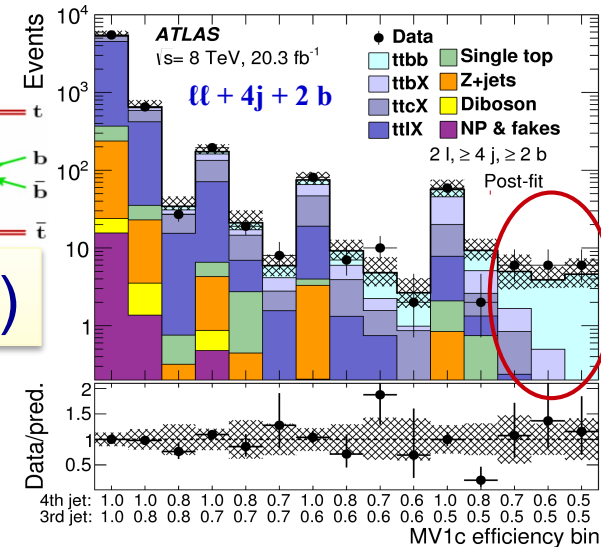
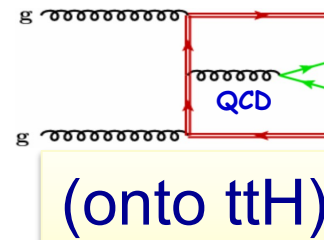
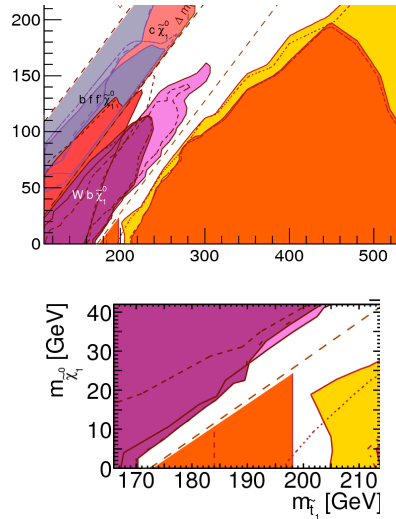
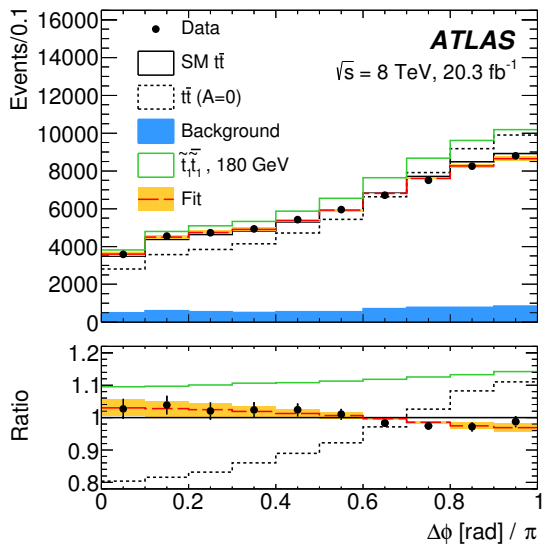
$$176 \pm 8(\text{stat}) \pm 10(\text{syst})$$

Many techniques, analysis methods, observations, born there... including: Matrix Element method; JES from W; not to mention bold usage of BDT for single t... And, of course, that b tag!

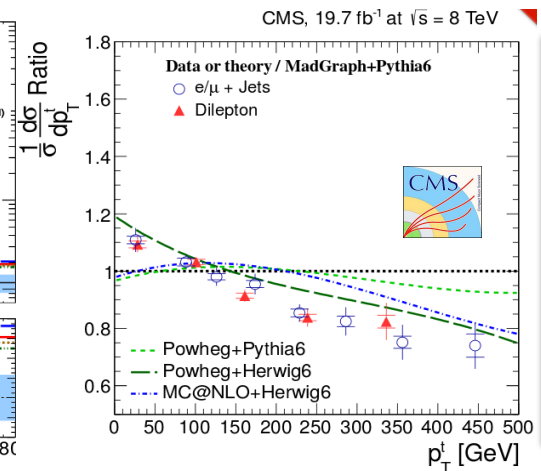
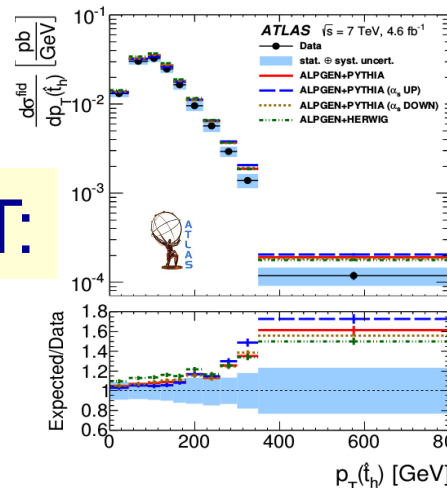
- The Tevatron experiments are completing legacy measurements
  - ▶ Precise cross section measurements
  - ▶ Precise measurements of the top quark mass
  - ▶ Final measurements of asymmetries in quark pair production
- Electroweak top production measurements are complete
  - ▶ Combination of t-channel cross sections
  - ▶ Observation of the s-channel production



# Top-quark studies at the LHC: “summary”



BUT:



Need  
some  
 $N^n\text{LO}$   
effort  
here...

Differential

Fiducial, Particle level

Full phase space, Parton level

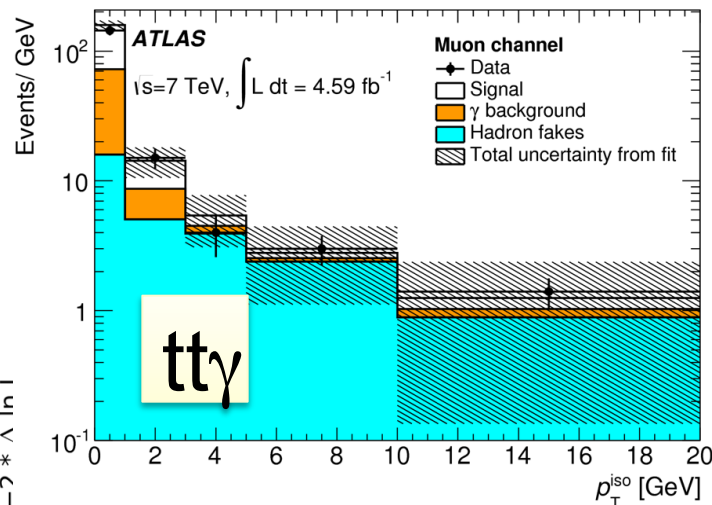
# ttV production

**Important bkg  
in several NP  
searches**

**+ several searches  
for FCNC:**

$t \rightarrow qZ$  ( $< 7 \times 10^{-4}$ )  
 $t \rightarrow qH$  ( $< 0.42 - 0.47$ )  
 $t \rightarrow qq$  ( $4 - 7 \times 10^{-7}$ )

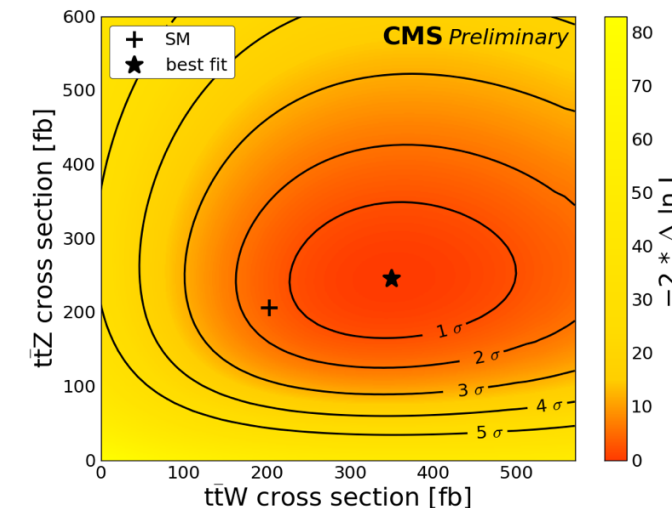
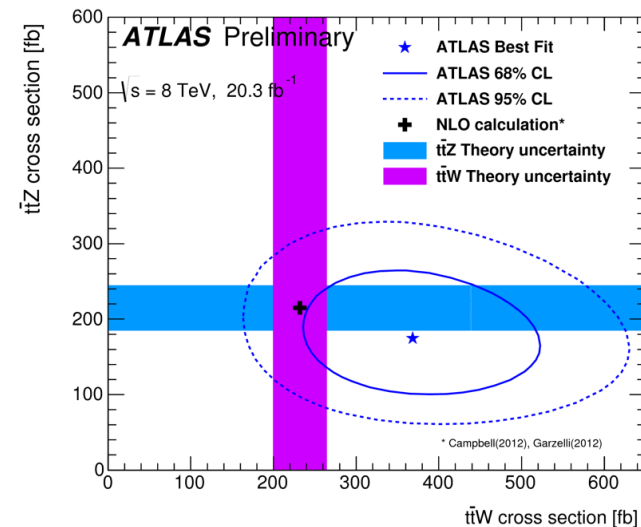
Proc/ Exp	ATLAS obs (exp)	CMS obs (exp)
ttW	5.0 (3.2)	4.8 (3.5)
ttZ	4.2 (4.5)	6.4 (5.7)



$$\sigma_{t\bar{t}\gamma}^{\text{fid}} \times \text{BR} = 63 \pm 8(\text{stat.})^{+17}_{-13}(\text{syst.}) \pm 1(\text{lumi.}) \text{ fb}$$

**SM:  $48 \pm 10$  fb**

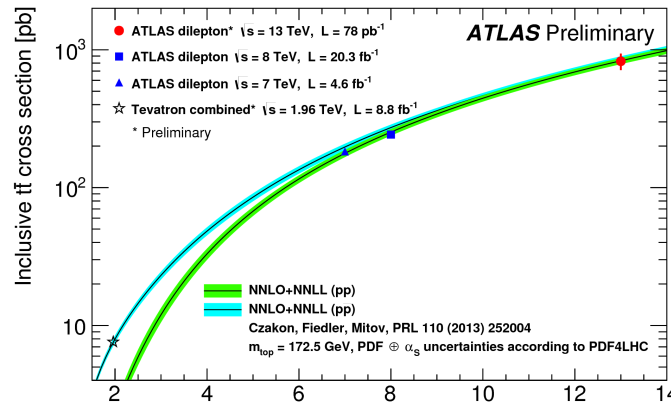
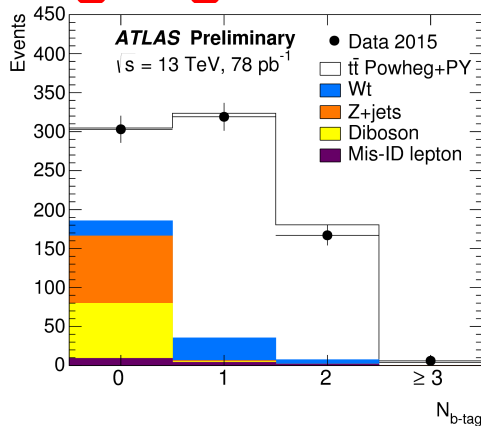
**5.3  $\sigma$**



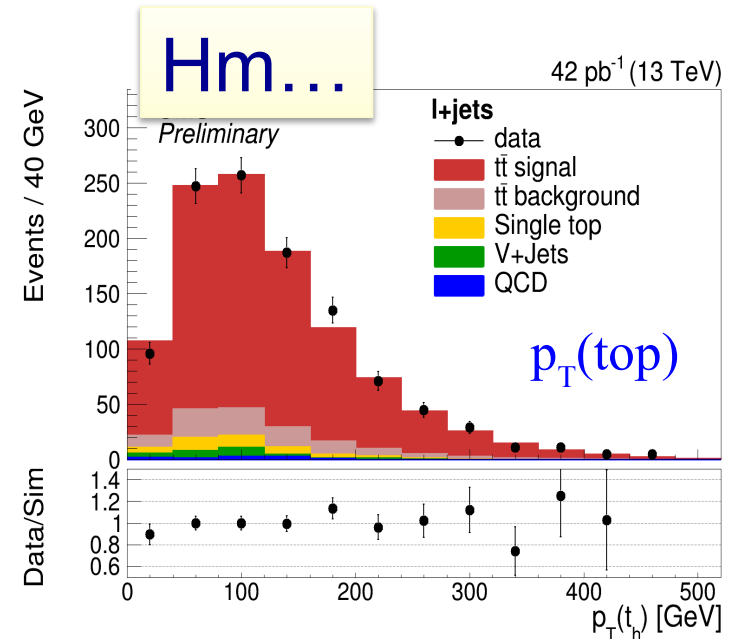
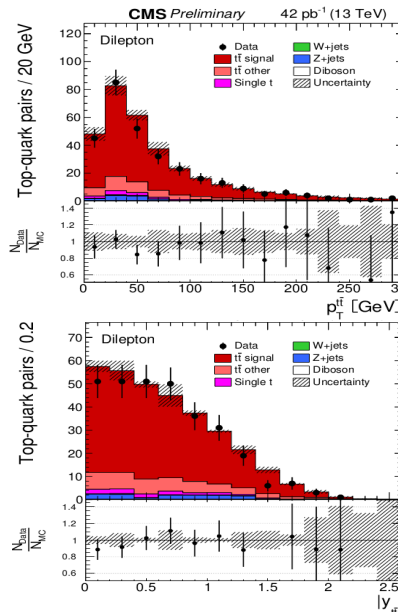
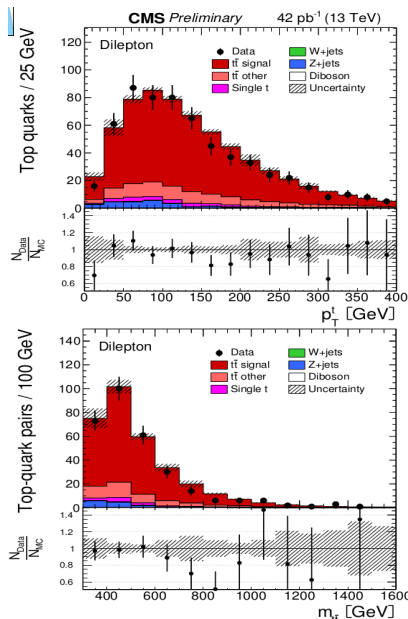


# t at 13 TeV

## Highlight: inclusive AND differential cross sections



$\sigma \approx 0.8 \text{ nb}$   
 Rate( $1.2 \times 10^{34}$ ):  
 1Hz (t factory) 😊



# Putting it all together: SM reigns supreme

## Goodness of fit

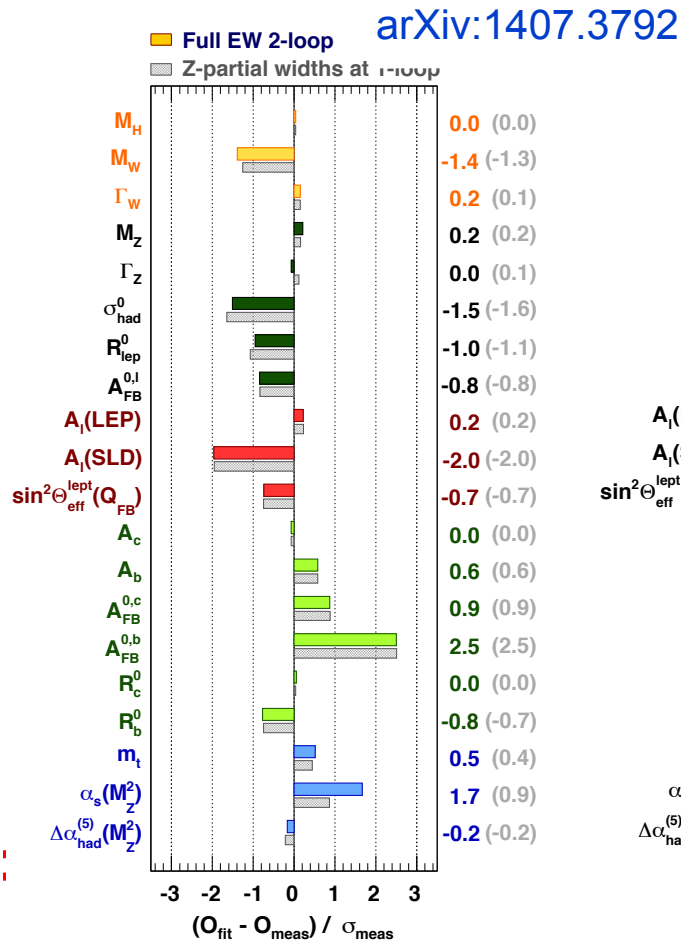
- ◆  $\chi^2_{\min} = 17.8$   
→ Prob = 21%

## Fit result often more accurate than measurement

- ◆ Small pulls for  $M_H$ ,  $M_Z$ ,  $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ,  $m_c$ ,  $m_b$  → input accuracies exceed fit requirements

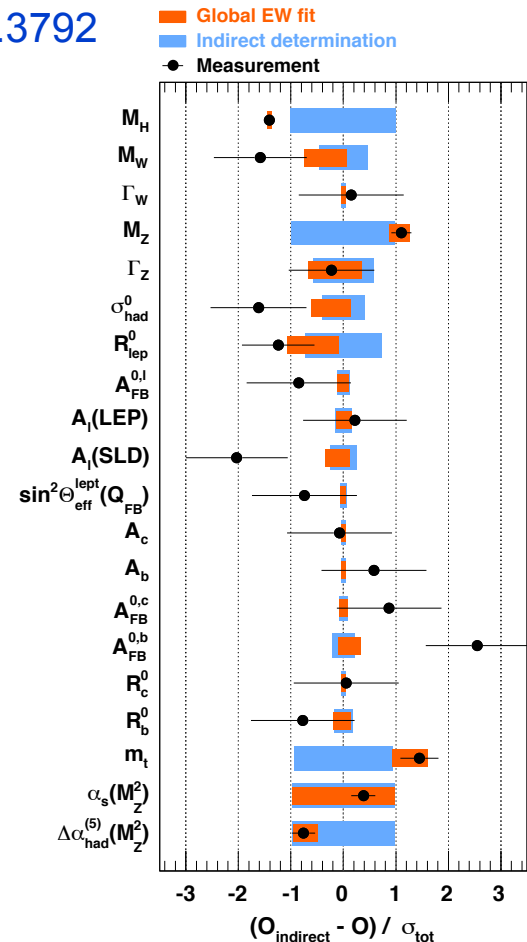
## Knowledge of $M_H$ → huge improvement in:

- ◆  $M_W$  (28 → 11 MeV)
- ◆  $m_t$  (6.2 → 2.5 GeV)
- ◆  $\sin^2\theta_W$  (2.3 →  $1.0 \times 10^{-3}$ )



**G** **fitter**

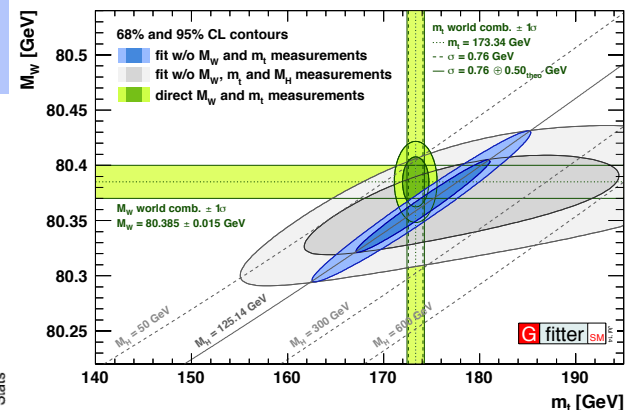
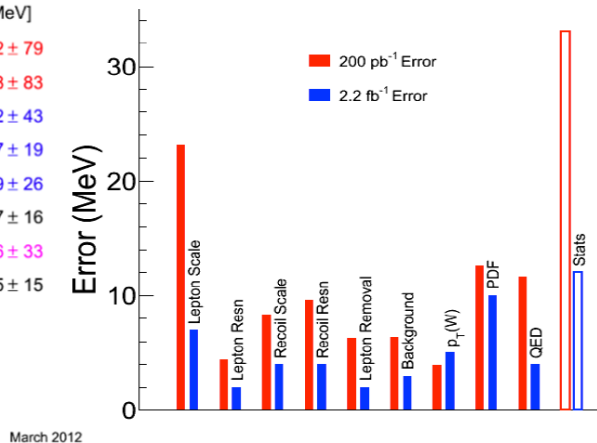
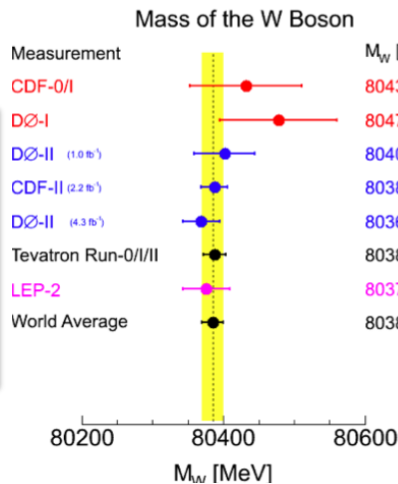
<http://cern.ch/Gfitter>



Light blue: fit excluding input from row

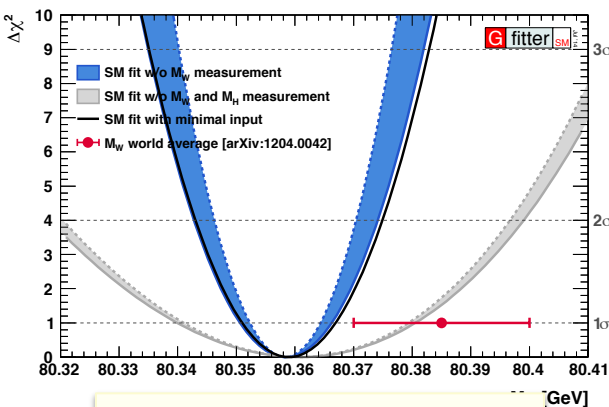
# Future? $M_W$ !

Tevatron  
Run II:  
halved  
 $\delta M_W$

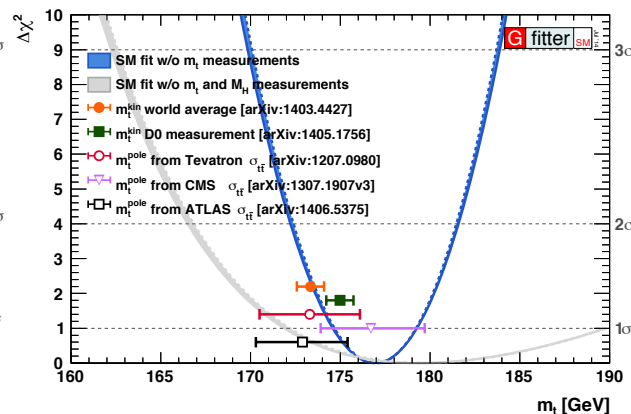


$$M_W = 80.358 \pm 0.008 \text{ GeV}$$

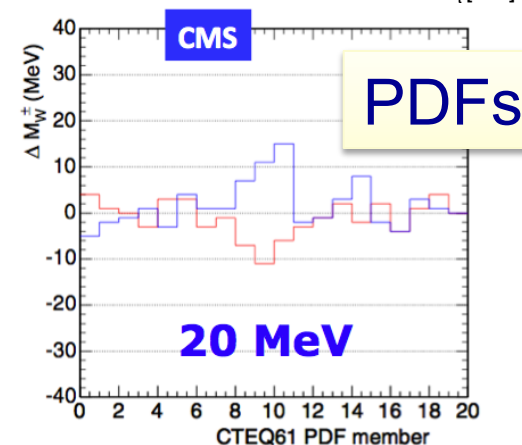
$$M_t = 177.0 + 2.3 - 2.4 \text{ GeV}$$



Calls for exptl  
measurement...



$$\delta(\text{exp}) < \delta(\text{theory})$$



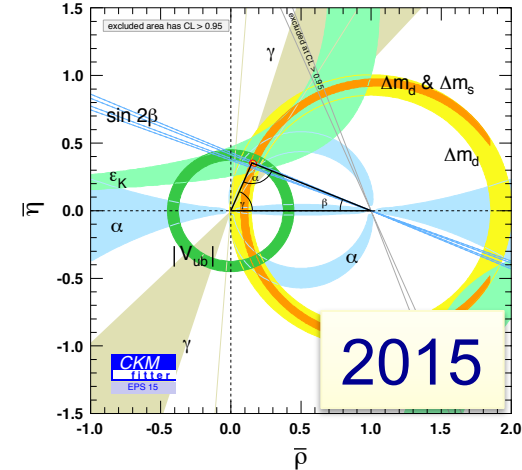
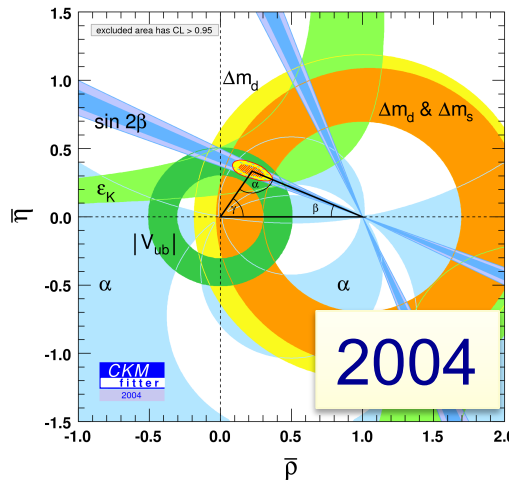
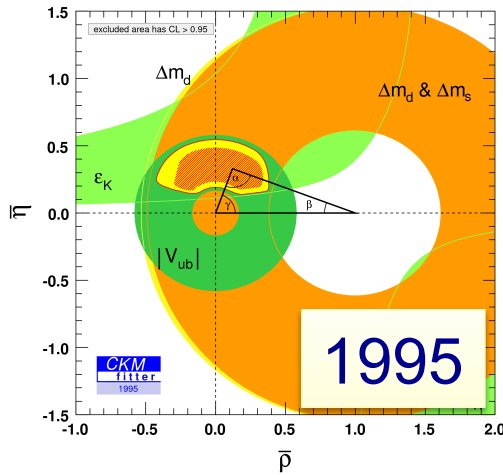
To constrain PDFs:  
 $y(Z)$ ;  $A_{\text{FB}}(W)$ ,  $A_{\text{FB}}(Z)$   
(both at TeV/LHC)

# **Our old-time friend: the Standard Model**

**Heavy Flavors:  
living a rich life in  $\sim 10^{-12}$  s**

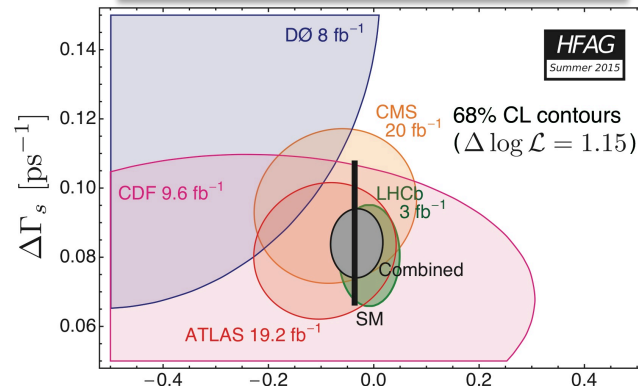
# Weak decays and the CKM

- Huge program of work → CKM “picture” established

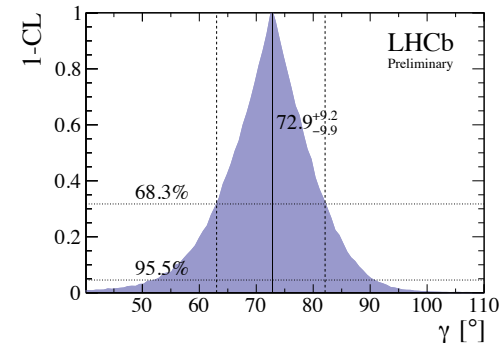


New measurements  
 $\sin 2\beta$ , mixing,  
 $\gamma$ ...

All is well:  $\phi_s \approx 0$



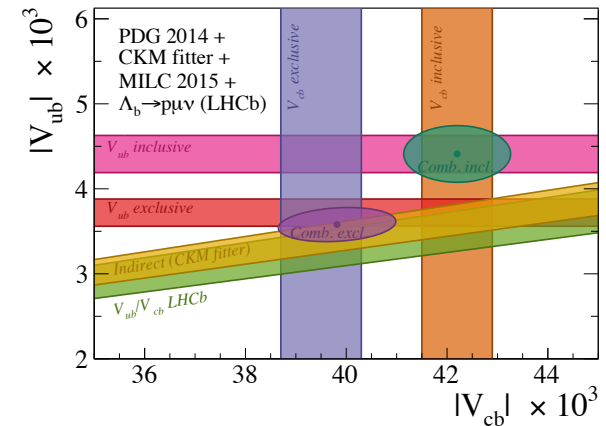
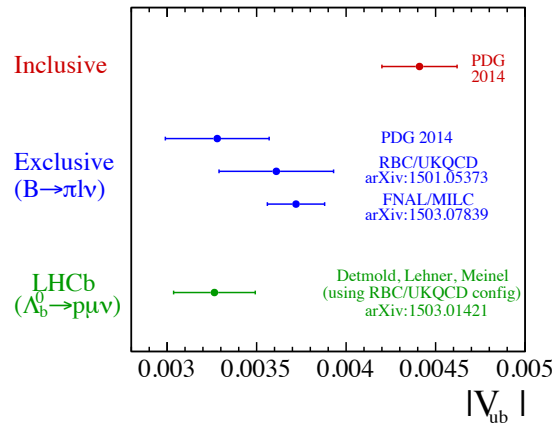
$B \rightarrow DK$



3fb<sup>-1</sup> update expected

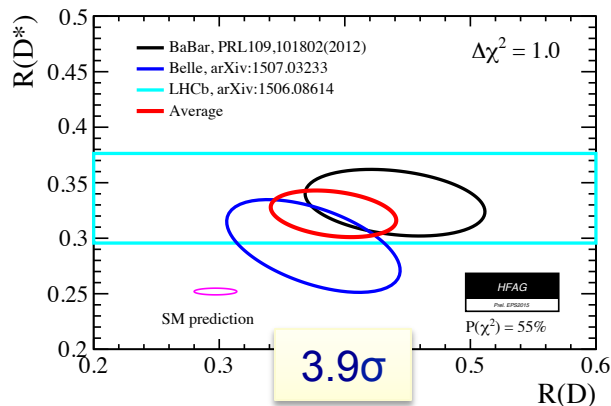
# Things to watch

■  $V_{ub}$ :  
 $\Lambda_b \rightarrow p \mu \nu$  in  
 line with  
 $B \rightarrow \pi \ell \nu$

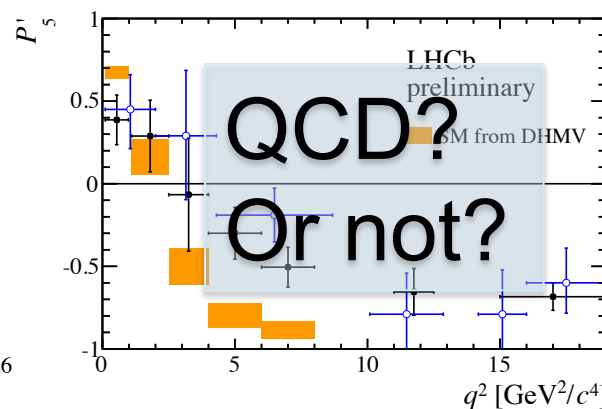


$V_{ub}$ : Given agreement with indirect determination (CKM triangle) and richness of  $D^{(*)}, (**)$  mass spectra, difficult to get too excited

$$R(D^{(*)}) \equiv \frac{\mathcal{B}[B \rightarrow D^{(*)} \tau \bar{\nu}_\tau]}{\mathcal{B}[B \rightarrow D^{(*)} \ell \bar{\nu}_\ell]} \quad (\ell = e, \mu)$$



$$B \rightarrow K^* \bar{\ell} \ell$$



Need/Expect rich set of measurements to probe these further:

Angular/differ meas. of

$$A_{FB}(\bar{\mu}\mu)/A_{FB}(\bar{e}e)$$

no-rate ratios, search for

$$B_q \rightarrow \bar{\ell} a \ell b, \quad B \rightarrow K^{(*)} \bar{\ell} a \ell b$$

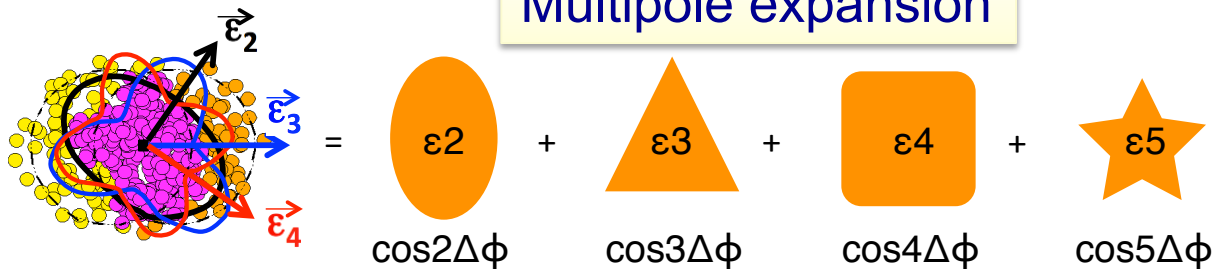
# **Our old-time friend: the Standard Model**

**Old-time friend:  
QCD with “free” partons**

# Heavy-ion physics: flow phenomena BARD (the nearly ultimate liquid)

$$\frac{d^3 N}{dy d^2 p_T} = \frac{d^2 N}{dy d p_T^2} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos(\phi - \psi_n) \right] \quad \psi_n = \frac{1}{n} \arctan \left( \frac{\langle p_T \sin n\phi \rangle}{\langle p_T \cos n\phi \rangle} \right)$$

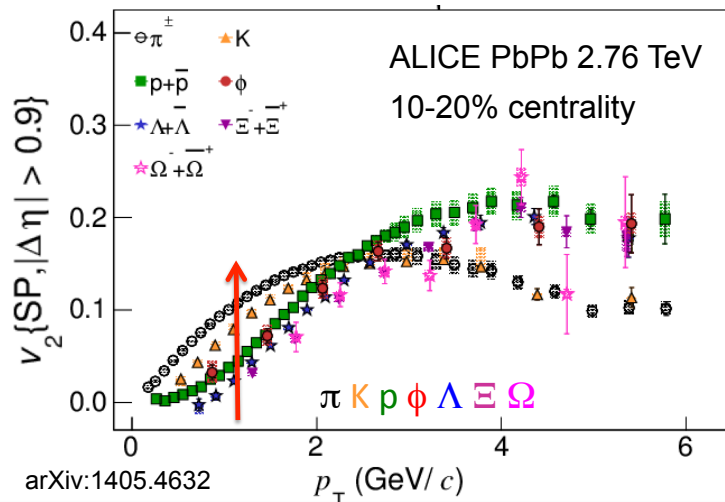
Multipole expansion



$v_1$  = Directed flow

$v_2$  = Elliptic flow

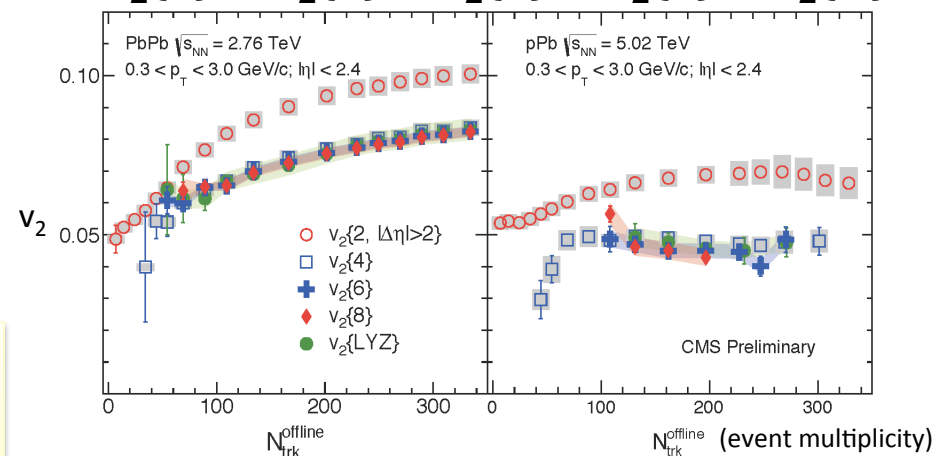
$v_3$  = Triangular flow



**Mass ordering:  $m \uparrow \rightarrow v_2 \downarrow$**   
 **$v_2(\text{baryons}) > v_2(\text{mesons})$  at high  $p_T$**

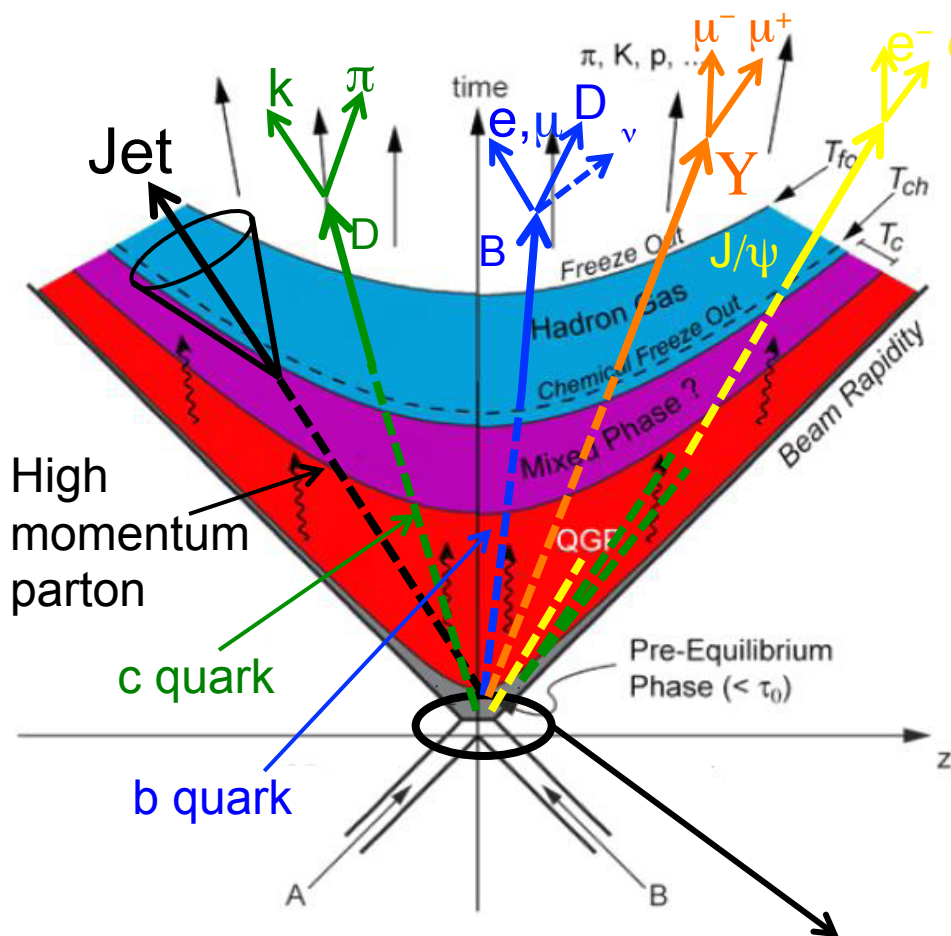
Hydrodynamics:

$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$$





# Heavy-Ion collisions: hard probes



## ■ Hard probes in nucleus-nucleus collisions:

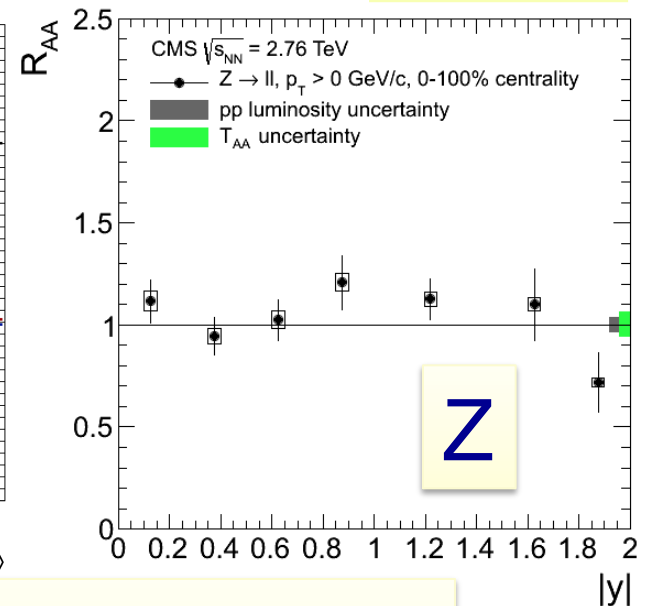
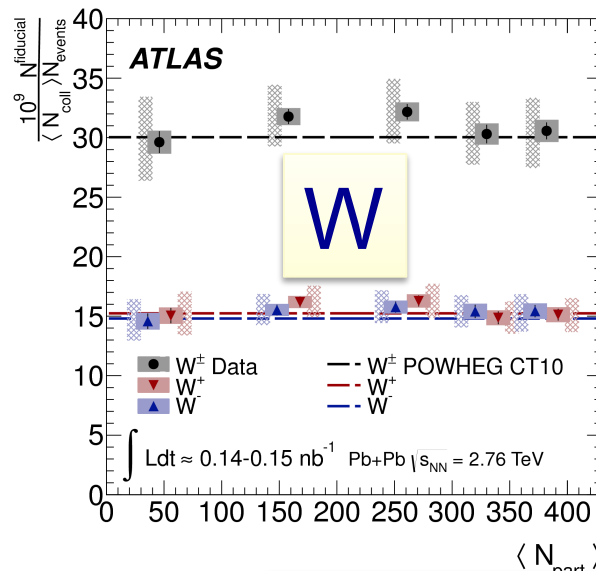
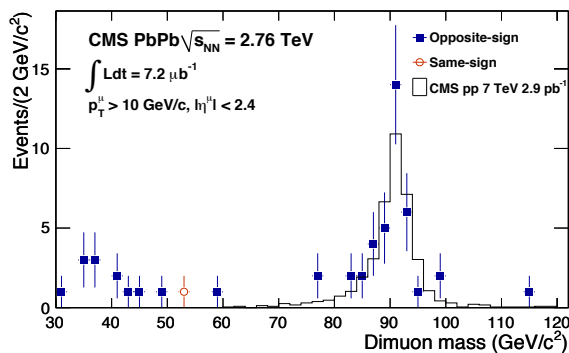
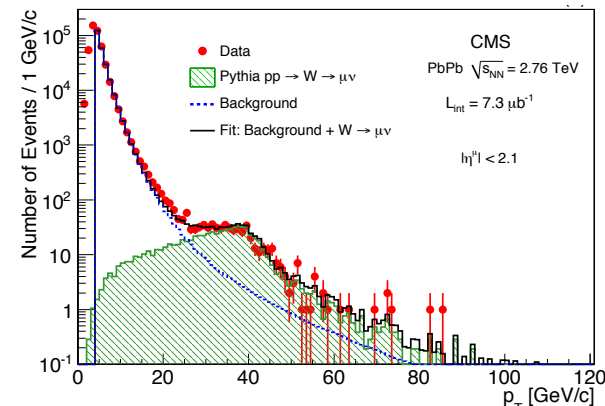
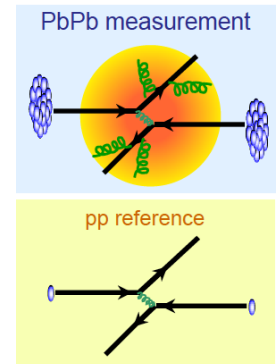
- ◆ produced at the very early stage of the collisions in partonic processes with large  $Q^2$
- ◆ pQCD can be used to calculate initial cross sections
- ◆ traverse the hot and dense medium
- ◆ can be used to probe the properties of the medium

G. Bruno

# Colorless probes

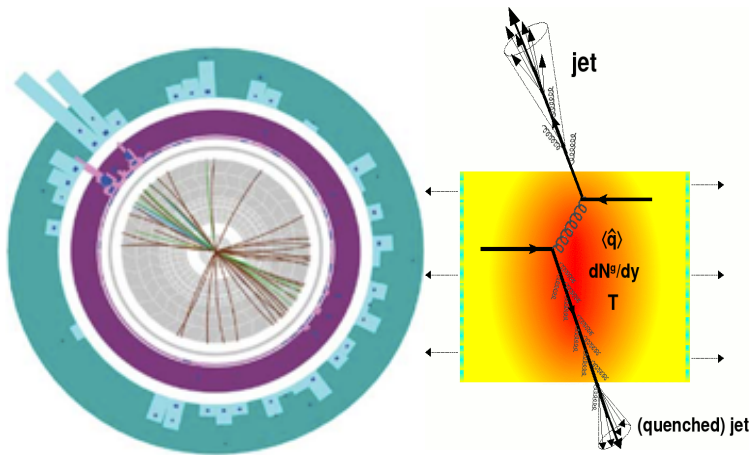
## Basic tool: the nuclear modification factor

$$R_{AA} = \frac{1}{N_{\text{coll}}} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA} / dp_T}{d\sigma_{pp} / dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

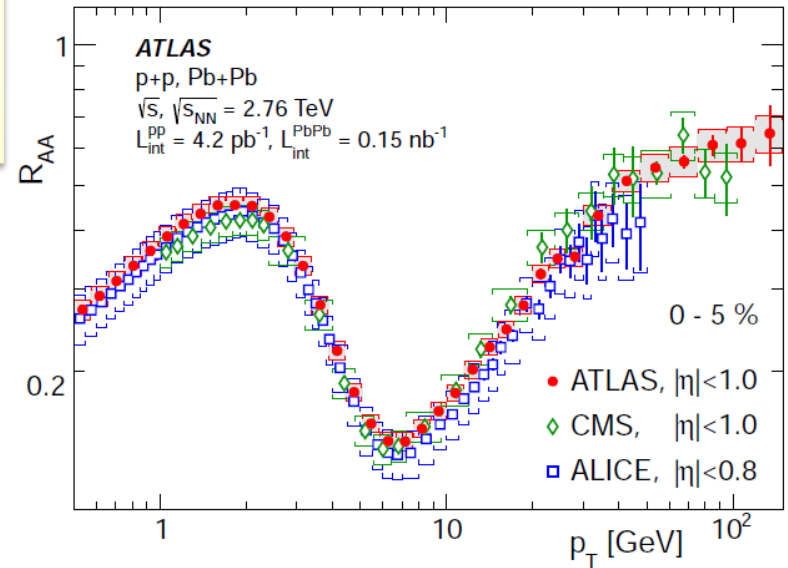


**W & Z bosons in Pb-Pb collisions scale like  $N_{\text{coll}}$**

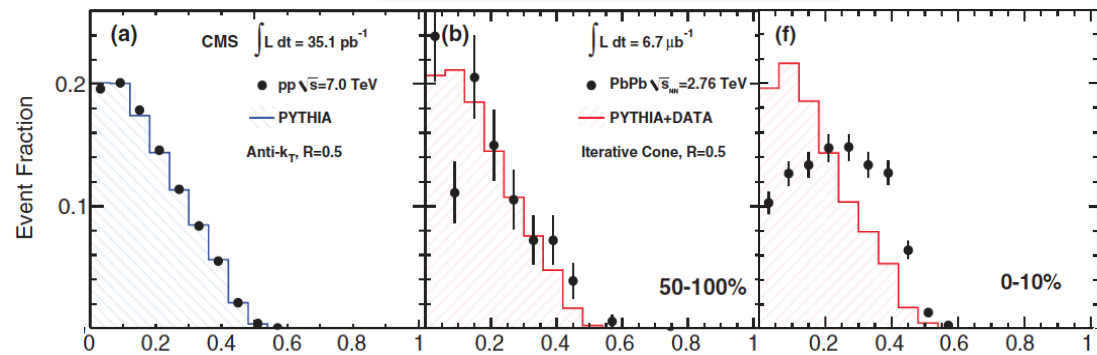
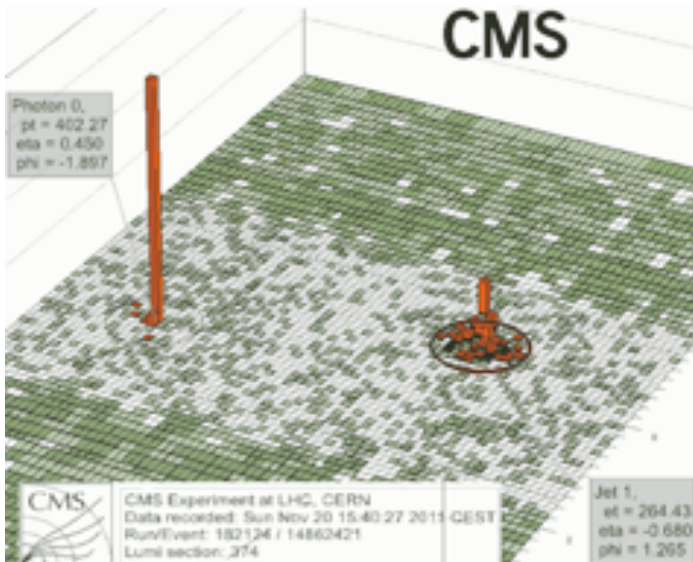
# Colorful probes → jets



hadron  
 $R_{AA}$



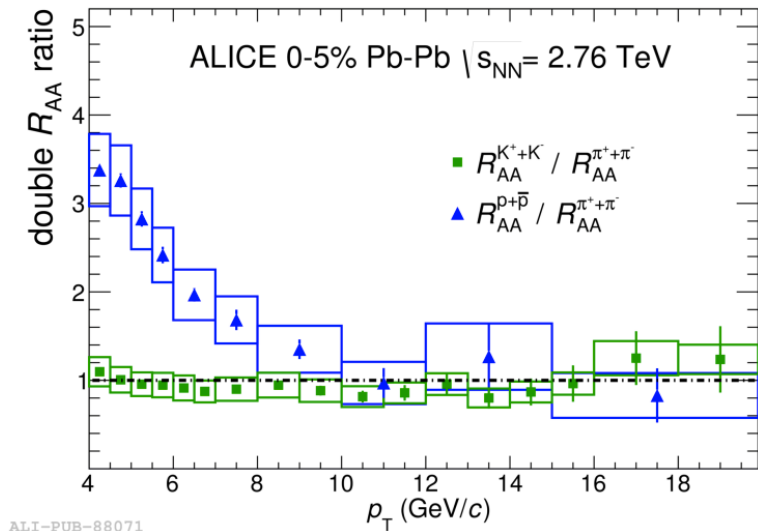
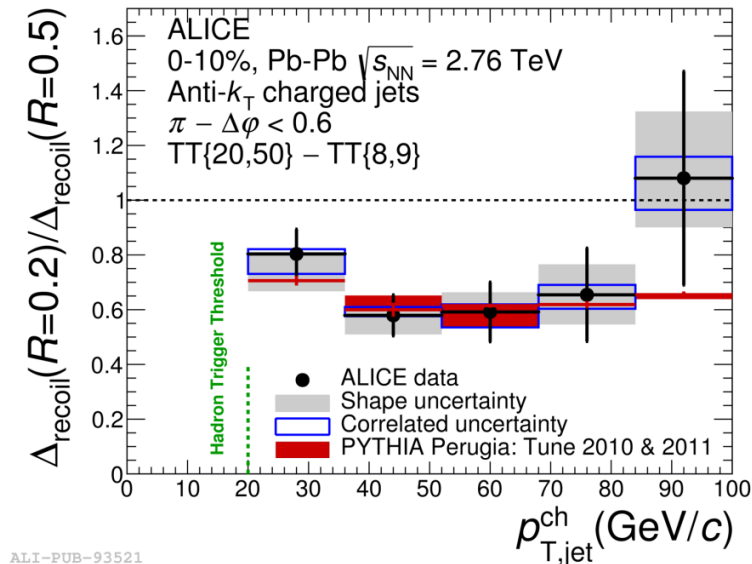
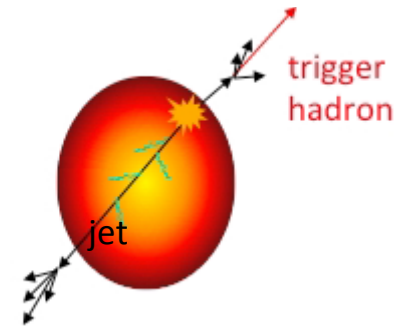
Jet quenching



# Jet studies

## How do the jets get modified?

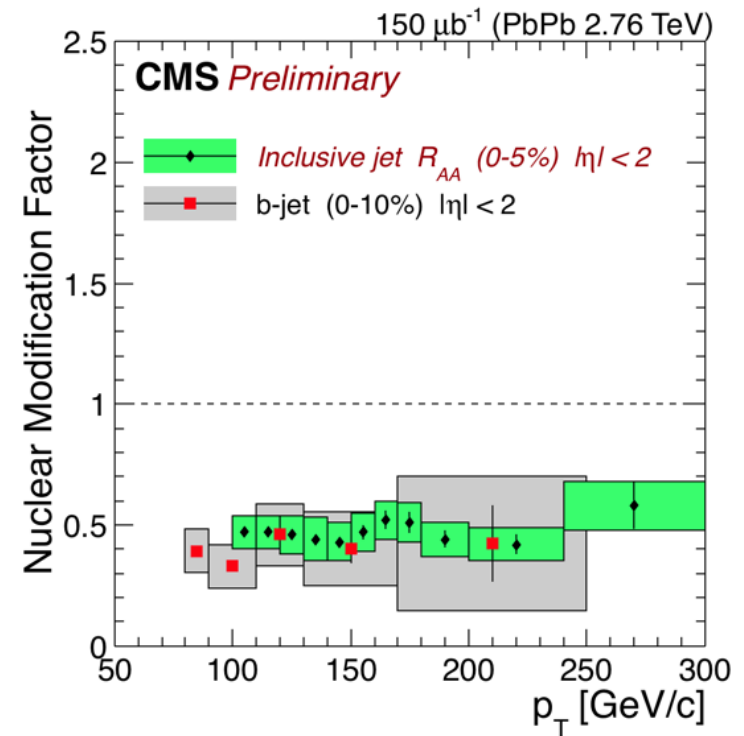
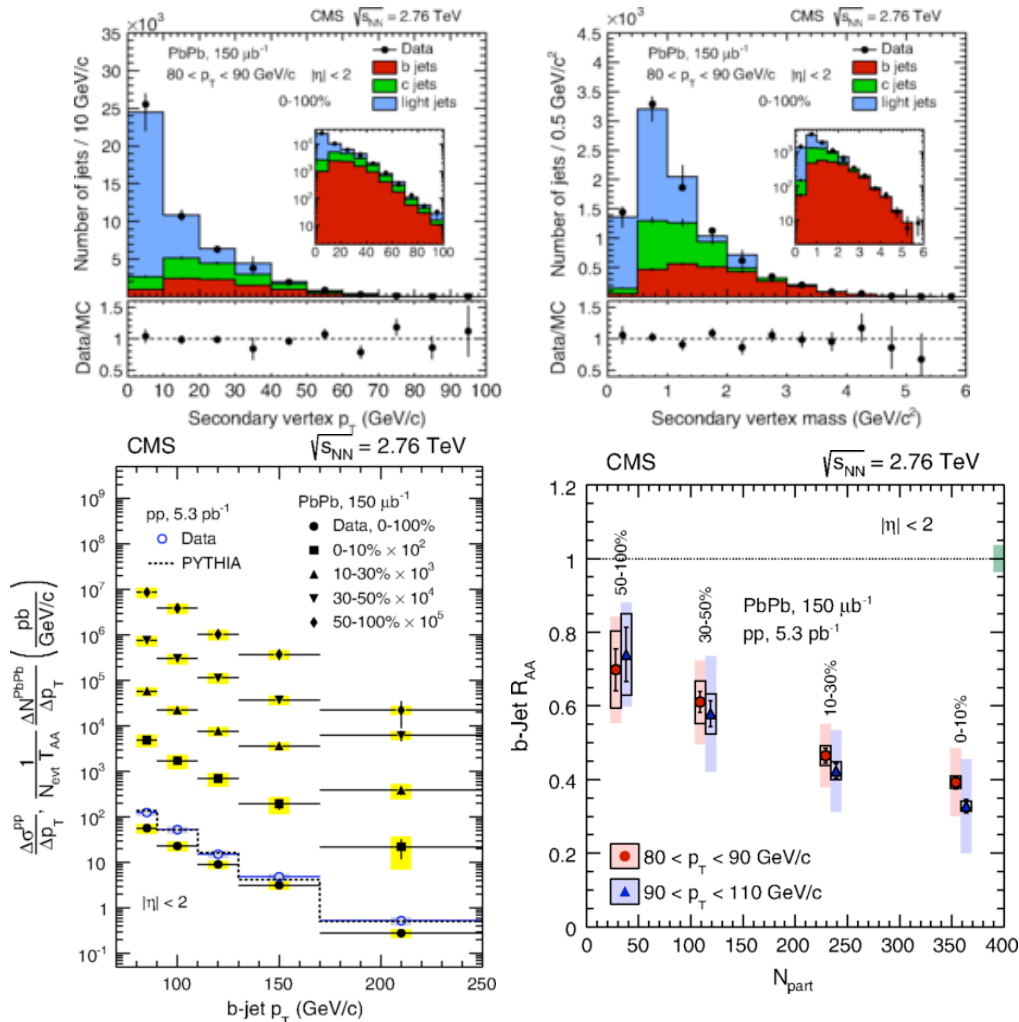
$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_{\text{T}}} \bigg|_{p_{\text{T,trig}} \in \text{TT}_{\text{Sig}}} - \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_{\text{T}}} \bigg|_{p_{\text{T,trig}} \in \text{TT}_{\text{Ref}}}$$



No change in “shape” for  $\Delta R \leq 0.5$

Same  $K/\pi$  and  $p/\pi$  in Pb-Pb and pp  
→ no change in leading particle

# Quenching of heavy flavors



**Quenching ~  
independent of flavor**

**Opens numerous new studies**

# **Our resilient “adversary”: the Standard Model**

**Where have all the  
New Physics signatures gone?**

# Solutions to the h-problem → signatures

- **All solutions demand the presence of new particles**
  - ◆ More Higgs bosons; SUSY partners; New W/Z bosons; new T, B
  - ◆ Once we speak of the “allowable”: even “Vector-Like Quarks”
- **Searches for new physics: main path has been the search for these (higher-mass) states**
  - ◆ In the beginning inclusively; as time goes by and searches come in empty-handed, ask “what/how” would have escaped?
    - And then tune analyses and go after specific signatures
- **Broadly speaking, five categories of searches:**
  - ◆ Searches for new resonances
  - ◆ Non-resonant: searches for SUSY (exemplified by MET)
  - ◆ Extending SUSY-like signatures: Dark Matter searches
  - ◆ Deviations from the QCD+EWK predictions (compositeness)
  - ◆ Exotica (e.g. long-lived “stuff”)

**Searches for non-resonant NP**



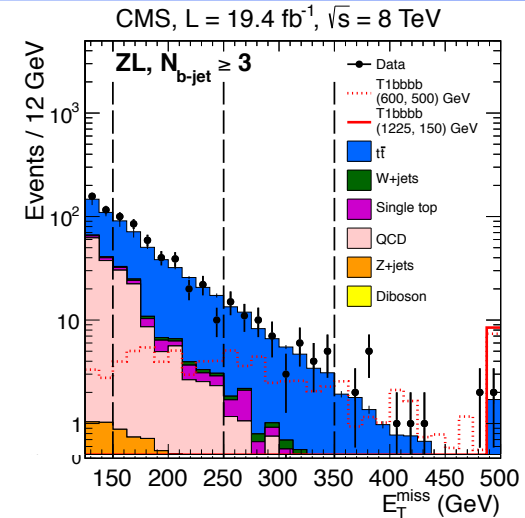
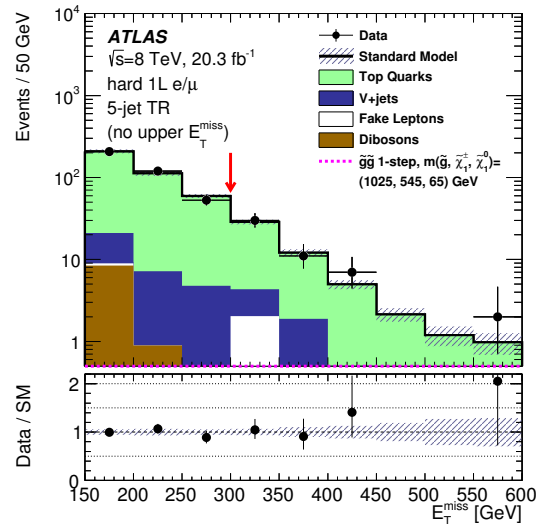
# SUSY: the (19)90's–(20)00's view

## SUSY Summary

---

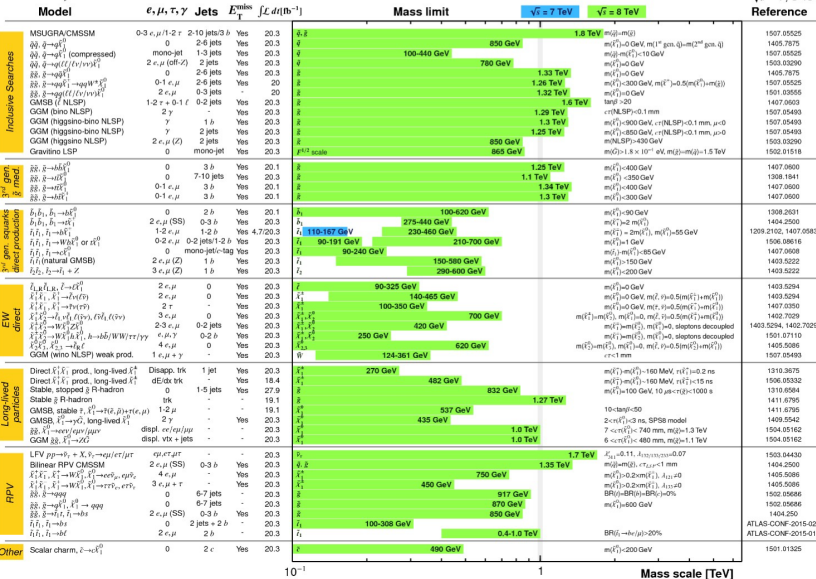
- SUSY discovery (should be) easy and fast
  - ◆ Expect very large yield of events in clean signatures (dilepton, diphoton).
    - Establishing mass scale is also easy ( $M_{\text{eff}}$ )
- Squarks and gluinos can be discovered over very large range in SUGRA space ( $M_0, M_{1/2}$ )  $\sim (2, 1)$  TeV
  - ◆ Discovery of charginos/neutralinos depends on model
  - ◆ Sleptons difficult if mass  $> 300$  GeV
  - ◆ Evaluation of new benchmarks (given LEP, cosmology etc) in progress
- Measurements: mass differences from edges, squark and gluino masses from combinatorics
- Can extract SUSY parameters with  $\sim (1-10)\%$  accuracy

# Then we got data, and she wasn't there



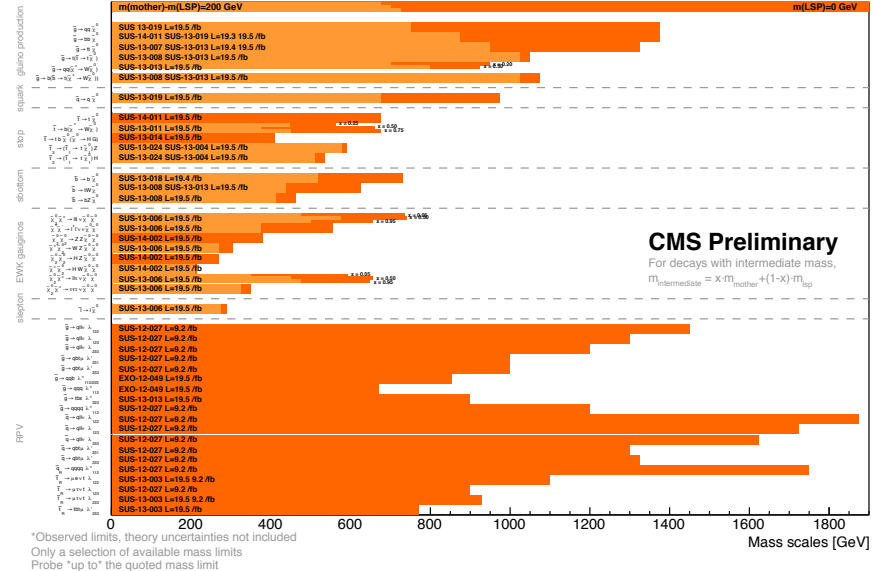
ATLAS SUSY Searches\* - 95% CL Lower Limits  
Status: July 2015

ATLAS Preliminary  
√s = 7, 8 TeV



Summary of CMS SUSY Results\* in SMS framework

IK



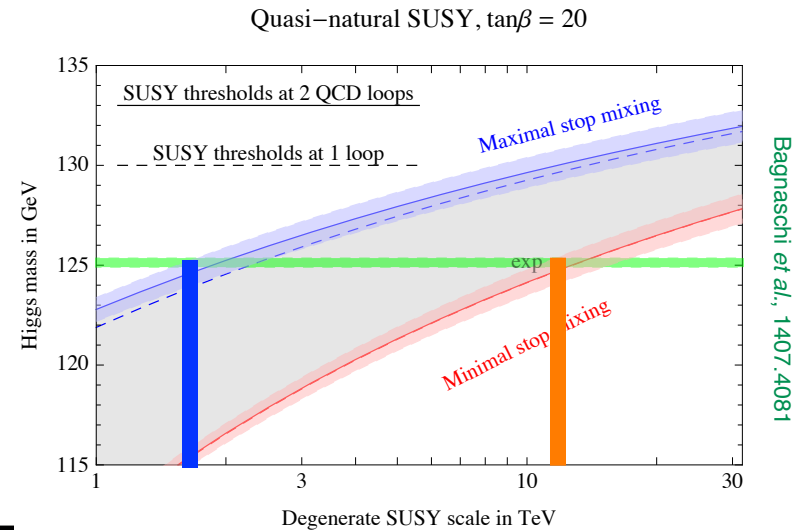
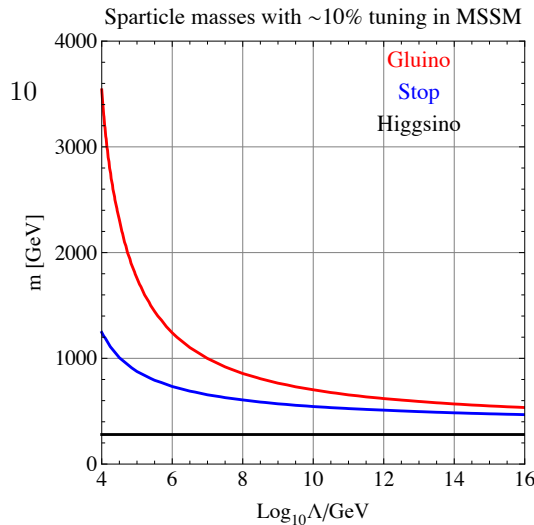
\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

# SUSY: impact of the Higgs

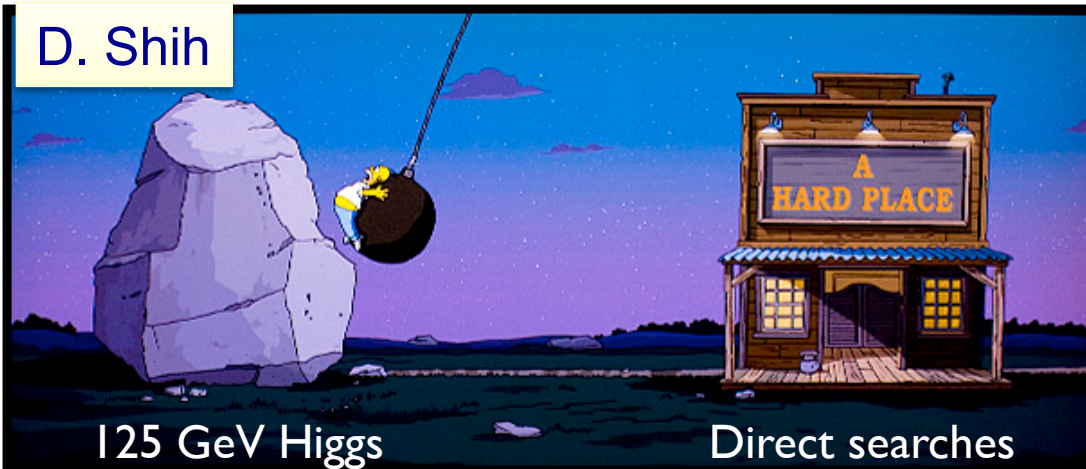
## ■ Squeezed (severely) by $m_H$ & lack of signs in searches

Theory/  
Orwellian  
definition of  
“natural”:

$$\Delta = \frac{2|\delta m_H^2|}{m_h^2} \leq 10$$



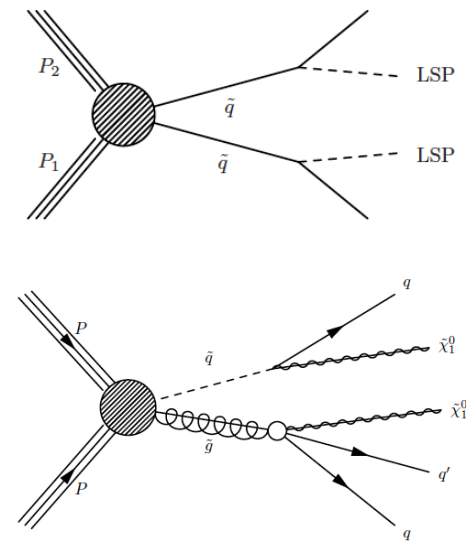
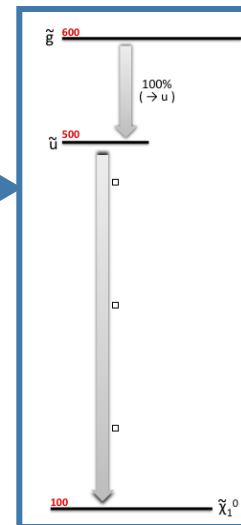
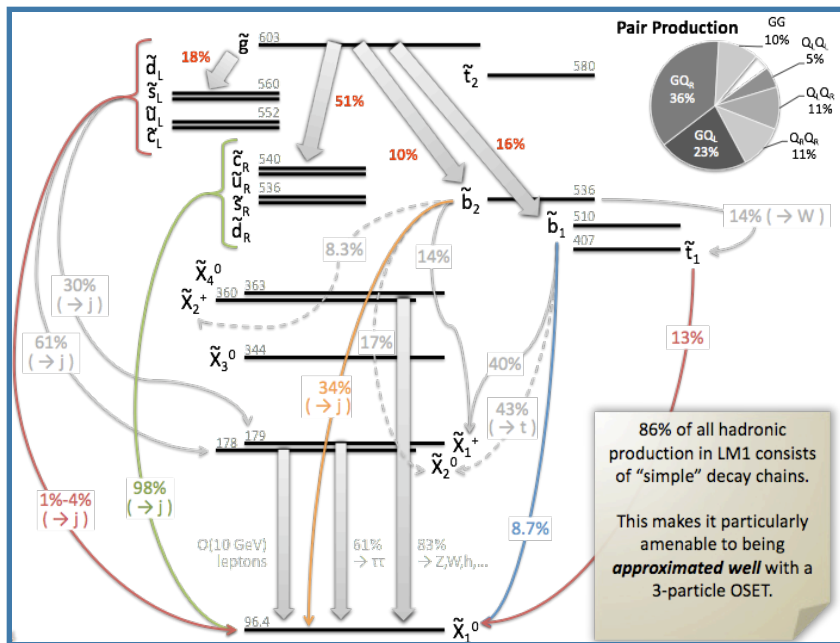
D. Shih



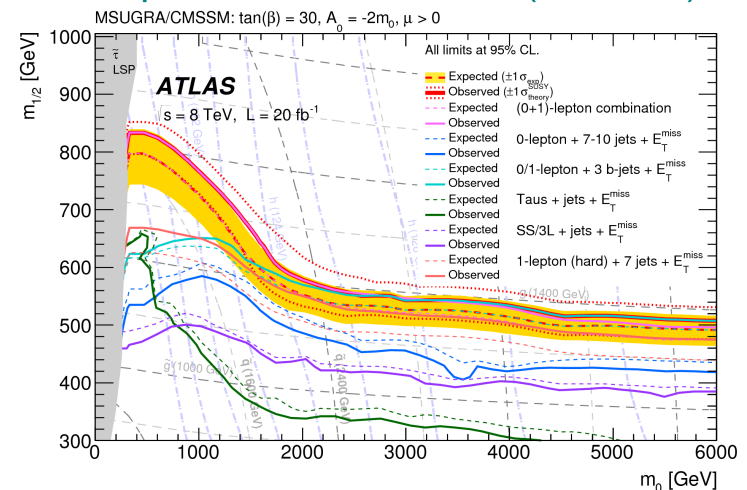
Optimist's view: high  $A_t$ .  
Theorist's view: not-so-easy  
to generate (large  $A_t$ )  
Experimentalist's view:  
clearly, an SEP\*

# SUSY: from the CMSSM to the SMS

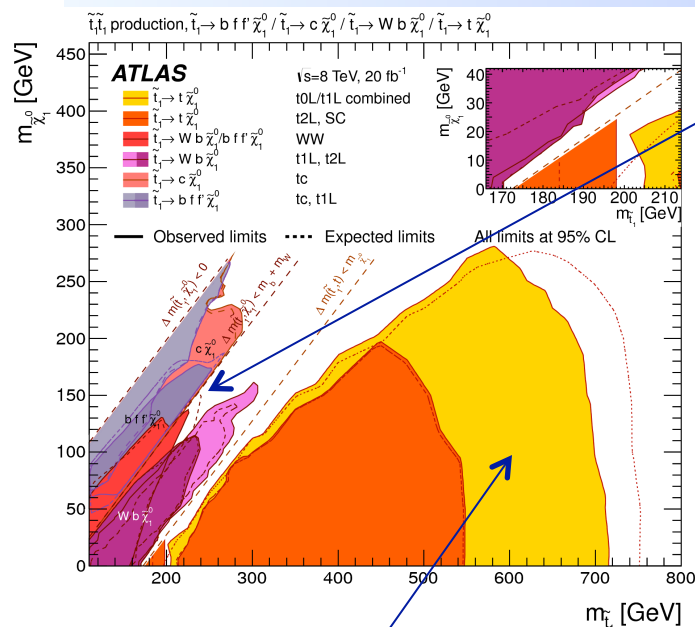
- **Experimentally: the CMSSM was very, very convenient.**
  - ◆ It also turned out to be wrong
  - ◆ And everyone cried out that this does not mean SUSY is not there
  - ◆ And thus, the SMS were born



## Specific SUSY Models (CMSSM)

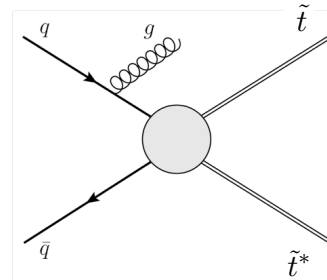


# Naturalness $\rightarrow$ 3<sup>rd</sup>-gen, EWKinos, et al

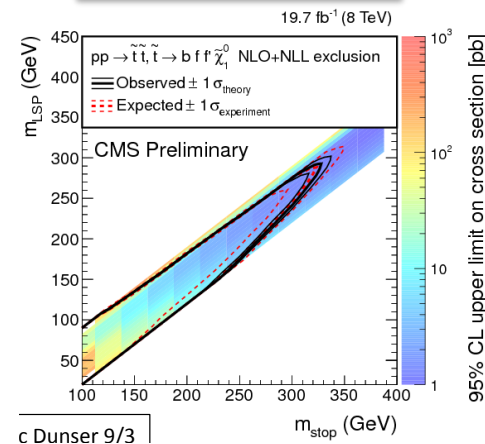


(a) Difficult Regions; impressive ingenuity in going after them (tech transfer  $\rightarrow$  DM)

ISR jets



Soft leptons

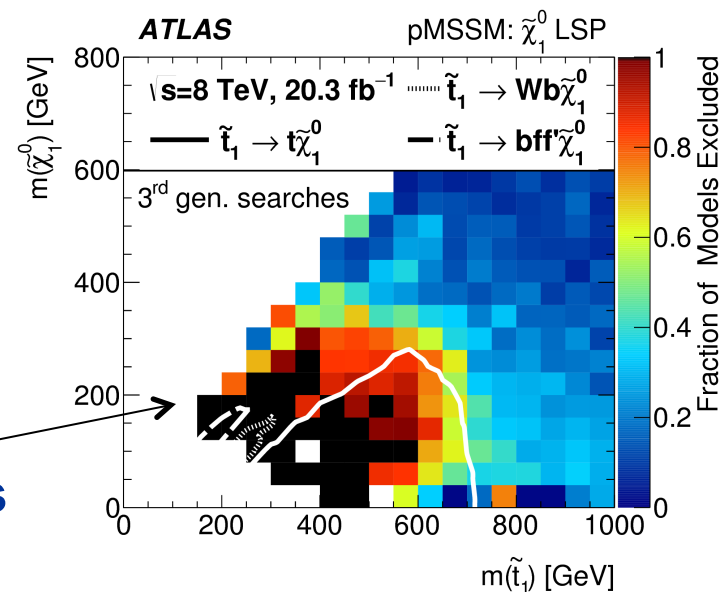


(b) Perhaps we overdid it (SMS)

♦ e.g. what if  $\chi^\pm$  in between the stop and the  $\chi^0$ ?

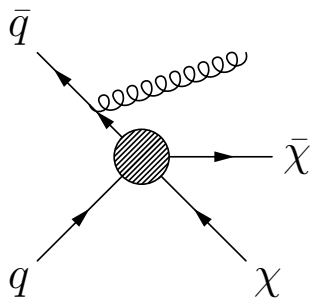
■ Use something between the vcCMSSM and the oSMS

♦ Enter the pMSSM; very nice analysis (300 kmodels; 30 GeV); e.g.

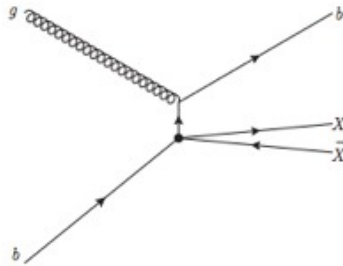


# **The Dark Sector**

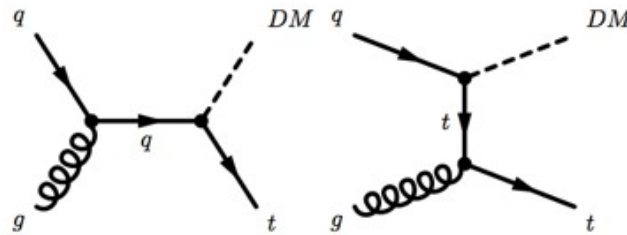
# Mono-X signatures



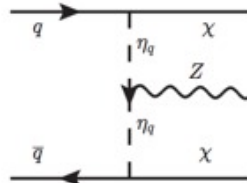
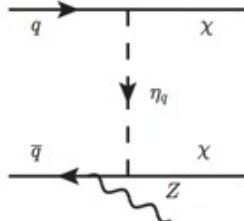
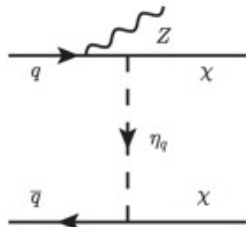
**Monojet**



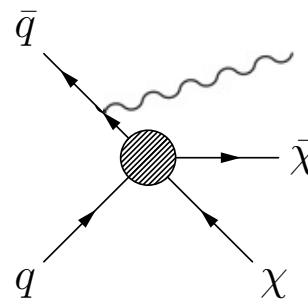
**MonoB**



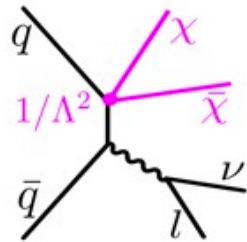
**MonoTop**



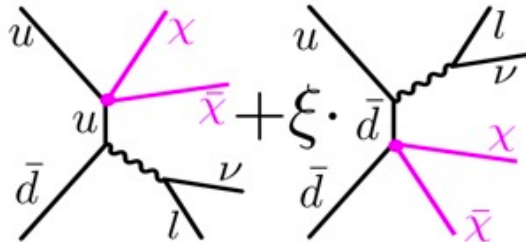
**MonoZ**



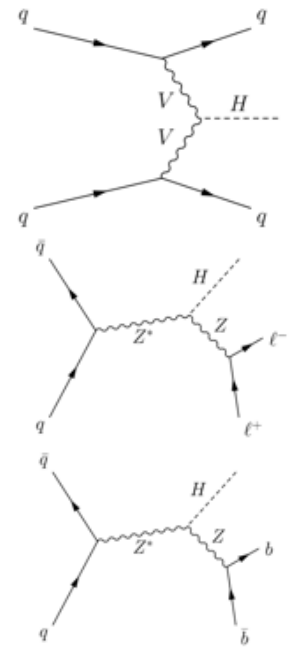
**MonoPhoton**



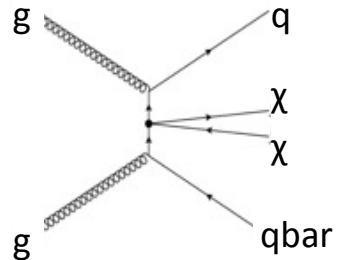
**MonoW (monoLepton)**



**MonoW/Z (Hadronic)**



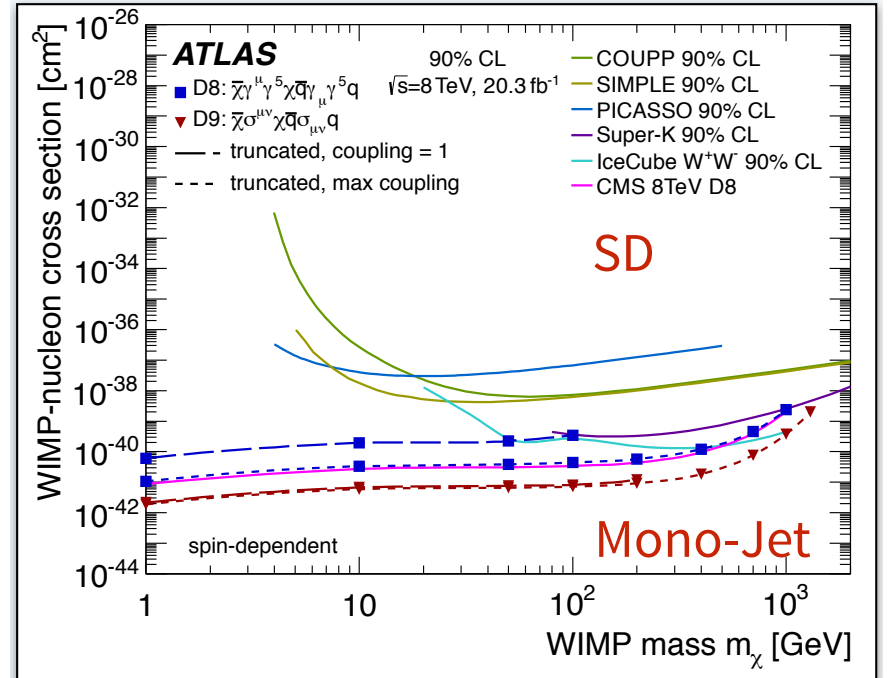
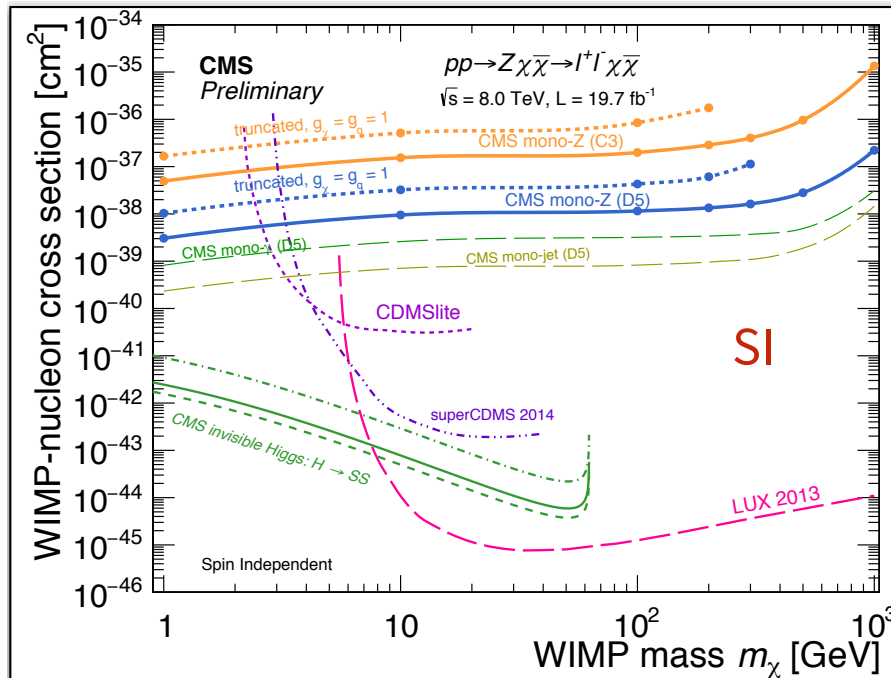
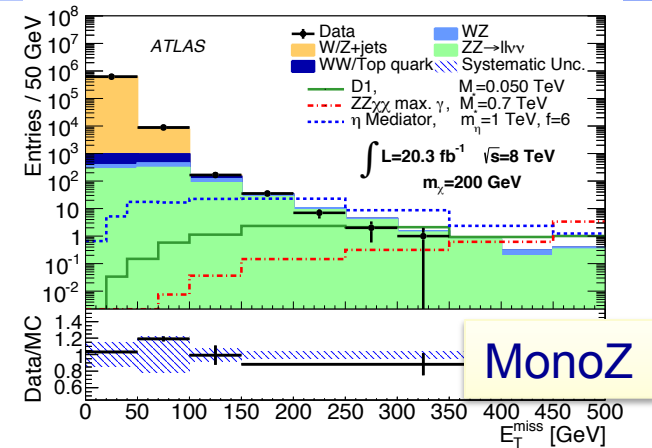
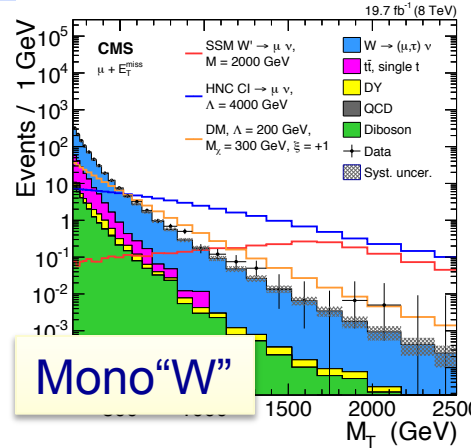
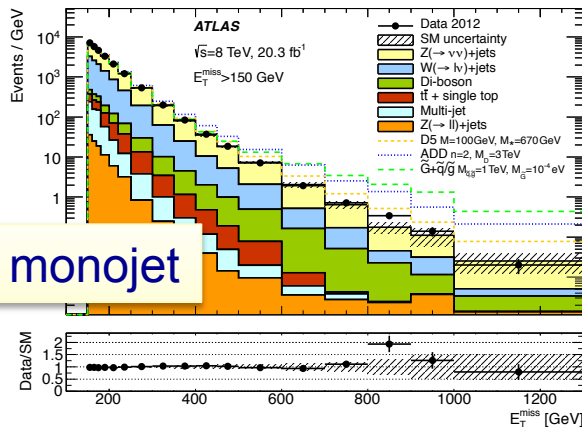
**Higgs Portal**



**BBbar /TTbar**



# No signal → limits on “traditional” plane

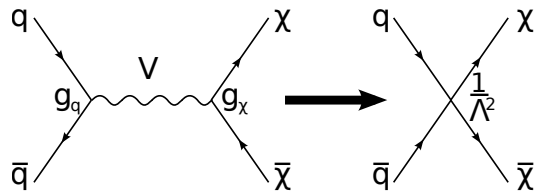




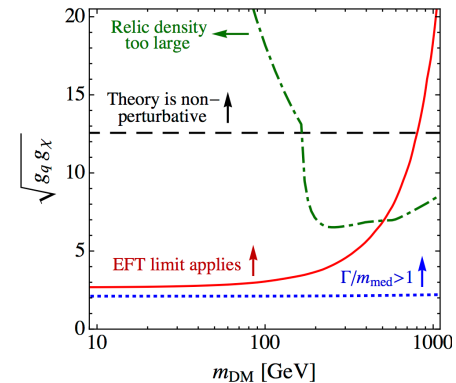
# From EFT to a Simplified Model

- (In)validity of EFT → need swift, joint action by Theory and Experiment:

- ◆ Add two parameters and mediator



$$\Lambda = \frac{M_V}{\sqrt{g_q g_\chi}}$$



- ◆ Make DM Forum (DM beware)

arXiv.org > hep-ex > arXiv:1507.00966

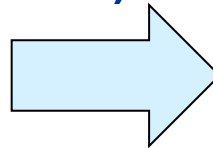
High Energy Physics - Experiment

## Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

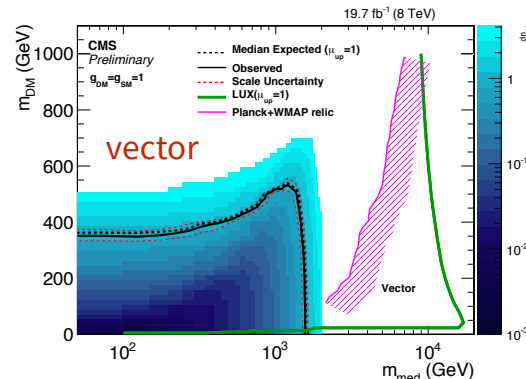
Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillermo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

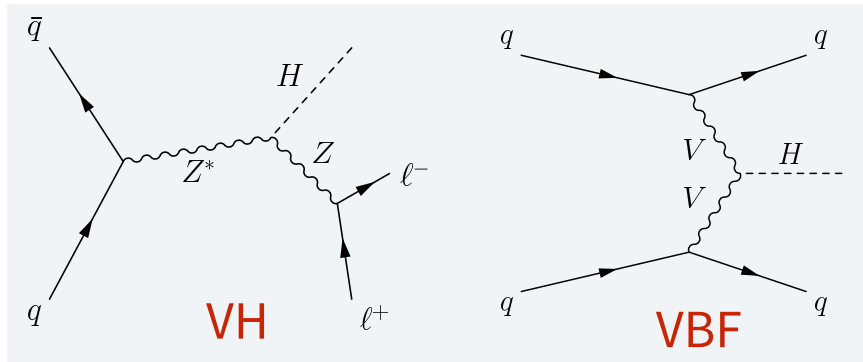


$m_\chi / \text{GeV}$	$M_{\text{med}} / \text{GeV}$									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000



What happens when one lets SUSY people in...

# Does the Higgs “see” DM?

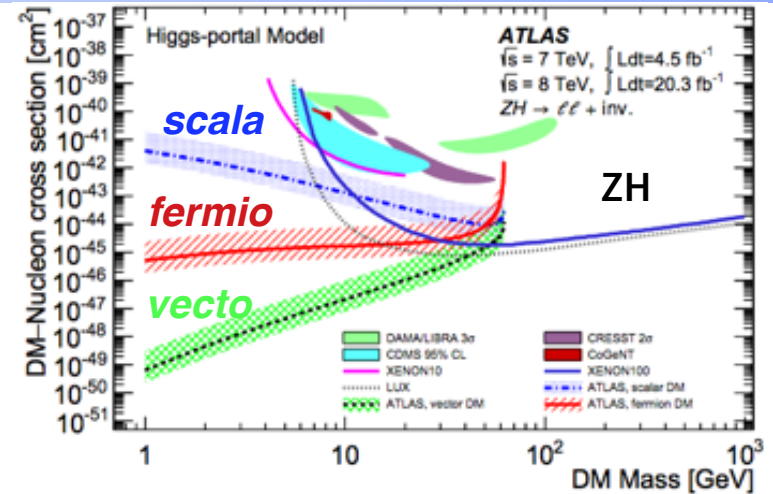
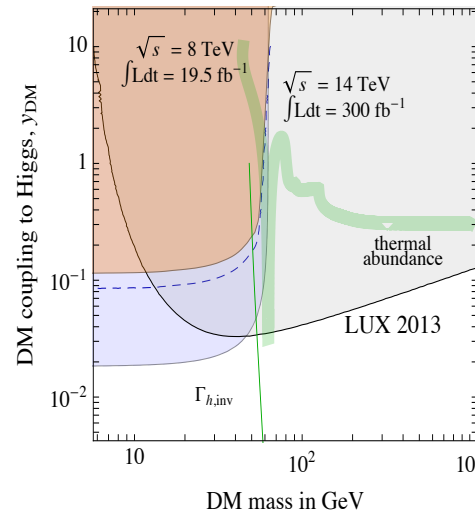
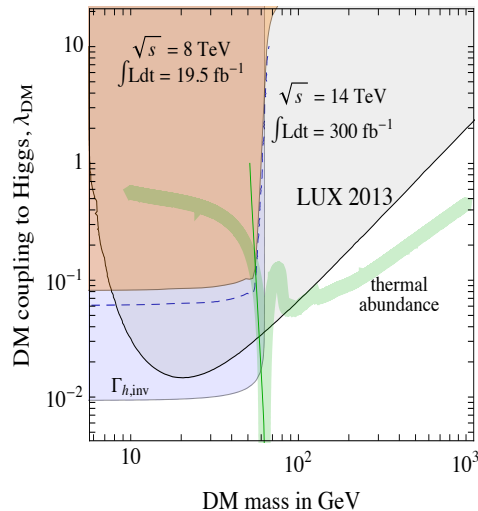


## ■ IFF Higgs is the mediator...

De Simone, Giudice, Strumia, 1402.6287

Scalar DM coupled to the Higgs

Fermion DM coupled to the Higgs



Then DM cannot be too light

Moreover, future searches (direct) will remove the  $M_H/2$  strip

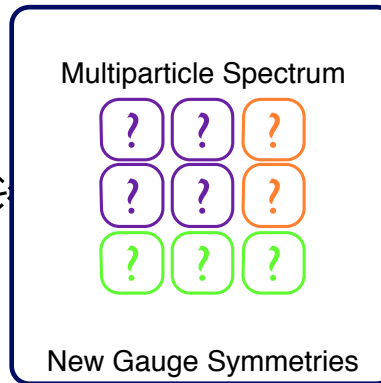
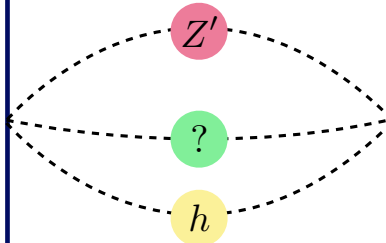
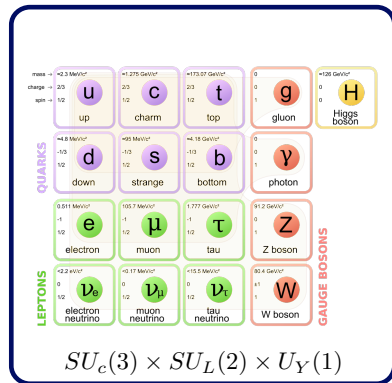
# The dark sector can have fun

- e.g. Dark Gauge Group:  $SU(4)_L \times SU(4)_R \times U(1)_X$  (NTBTS)

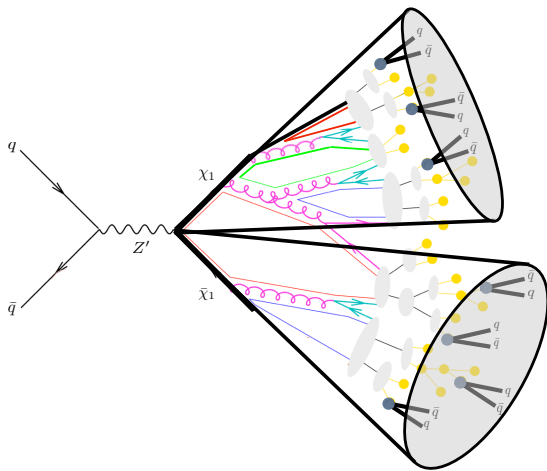
Visible Sector

Portal

Dark Sector

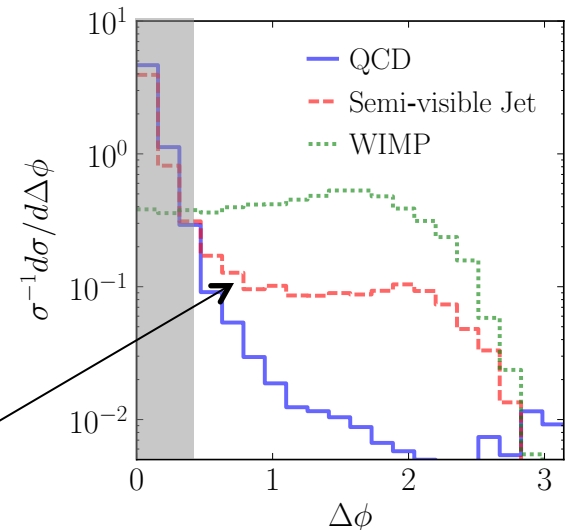


The revenge of SUSY ☺: defines all particles, spins & couplings...



“Semi-Visible jets”, aka “revenge of the theorists”

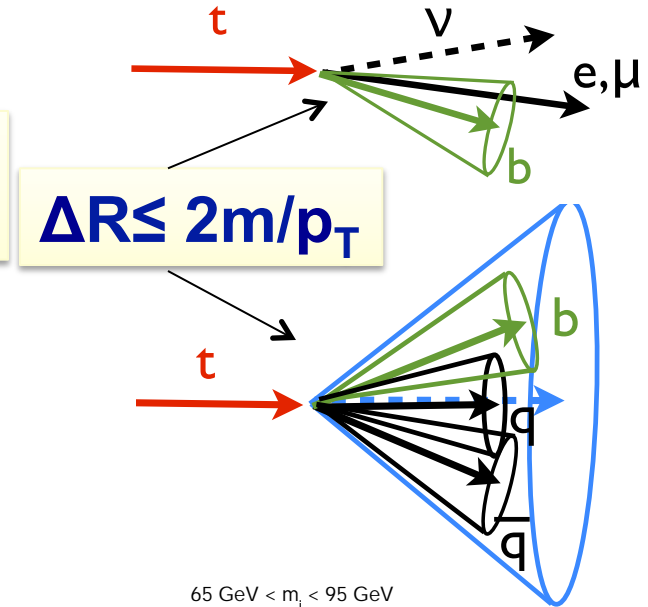
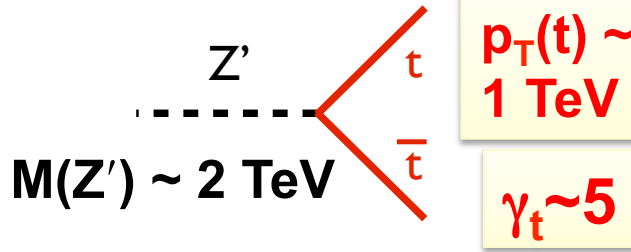
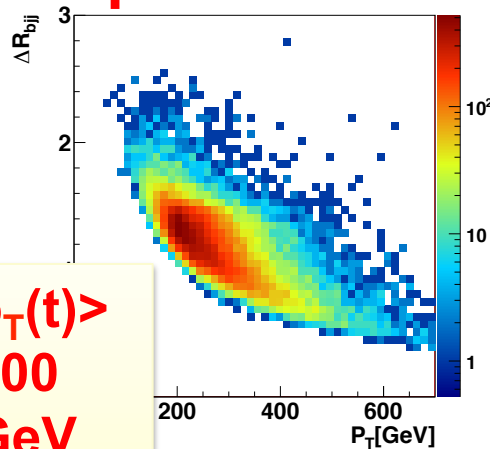
$\sim 70\%$  WIMP  
 $\sim 7\%$  Semi-visible jet



**Searches for resonant NP**

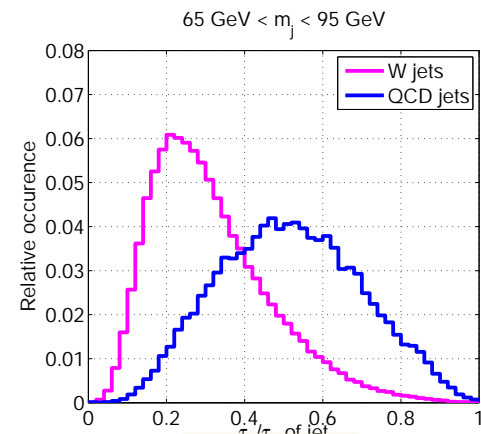
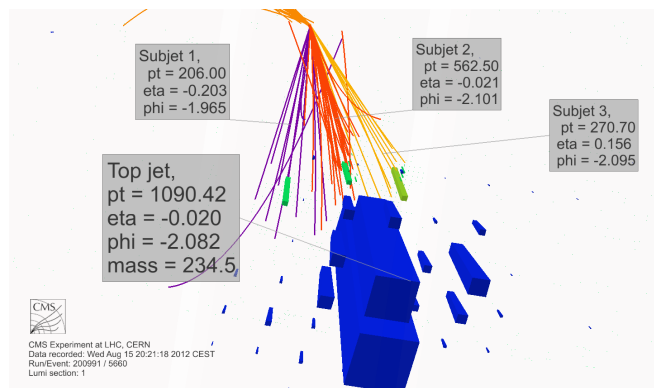
# Jet substructure (I)

- At high boost, decay products collimated;



$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k} \}$$

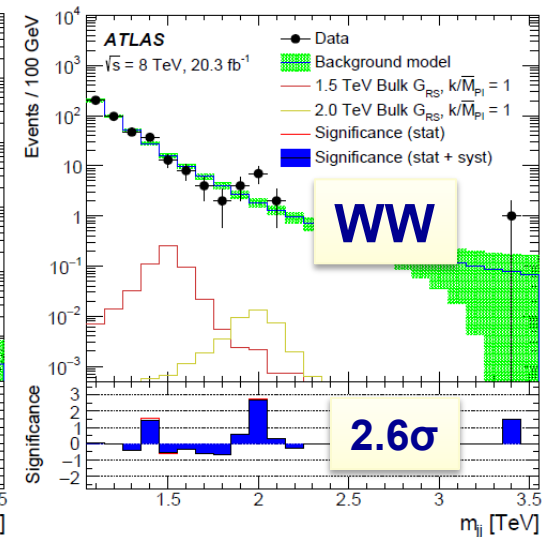
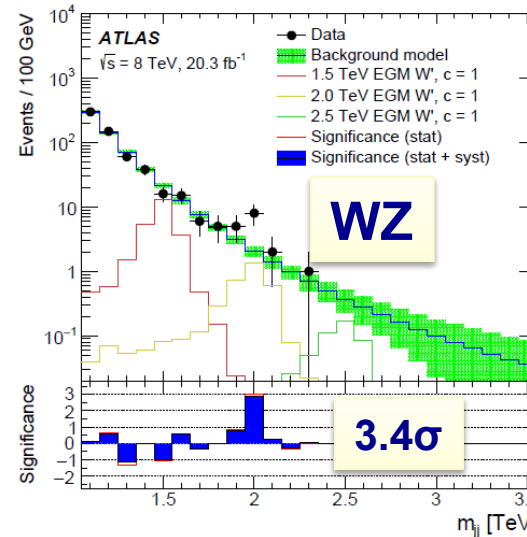
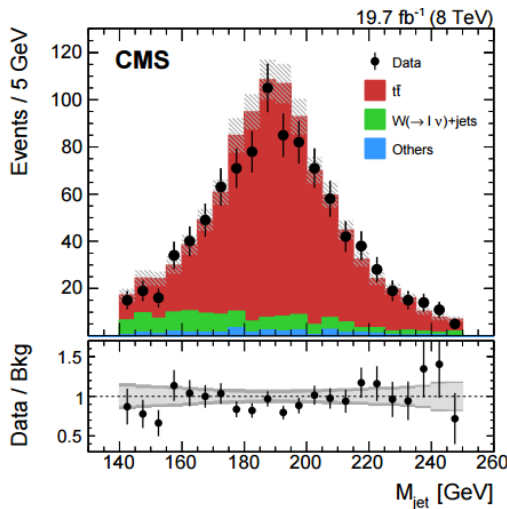
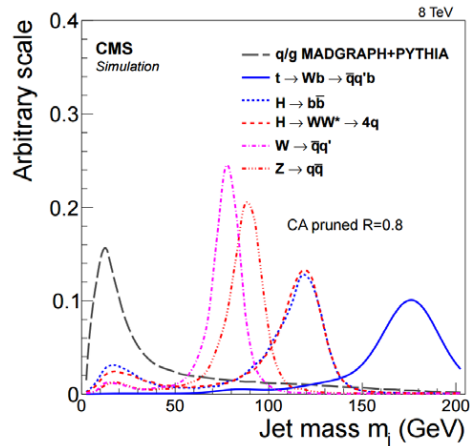
$$d_0 = \sum_k p_{T,k} R_0$$



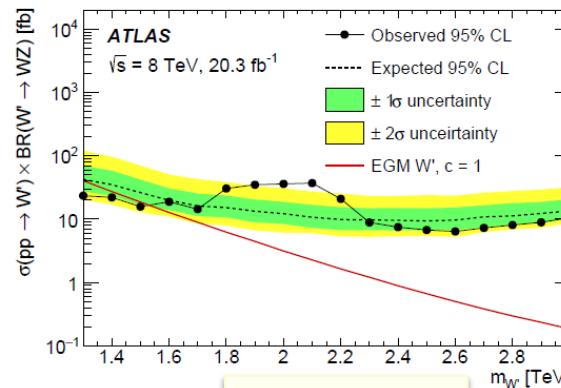
$$\tau_2/\tau_1$$

# Resonances decaying to VV, with $V \rightarrow \text{jets}$ ?

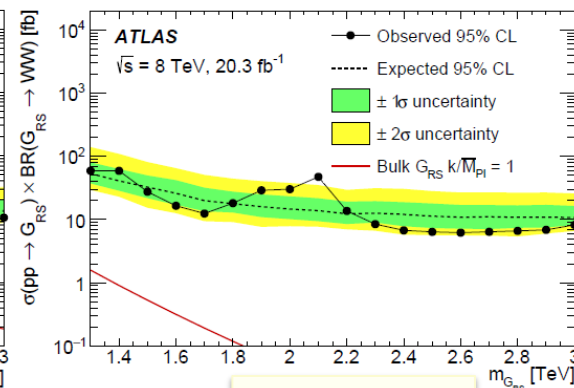
## Major new tool: jet substructure



To the innocent slide reader: large overlap in events...

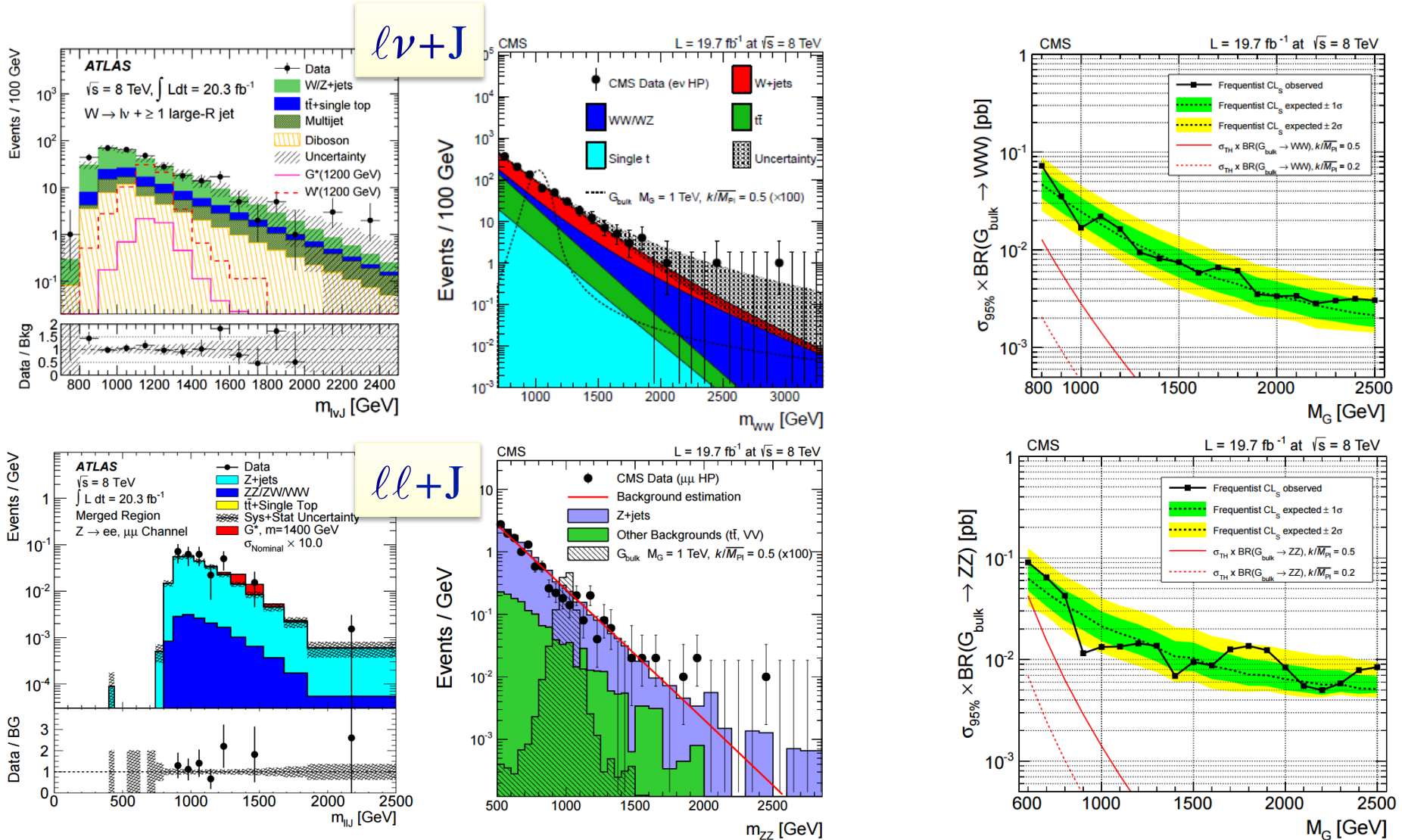


$W' \rightarrow WZ$



$G_B \rightarrow WW$

# Turning fast to leptonic modes...

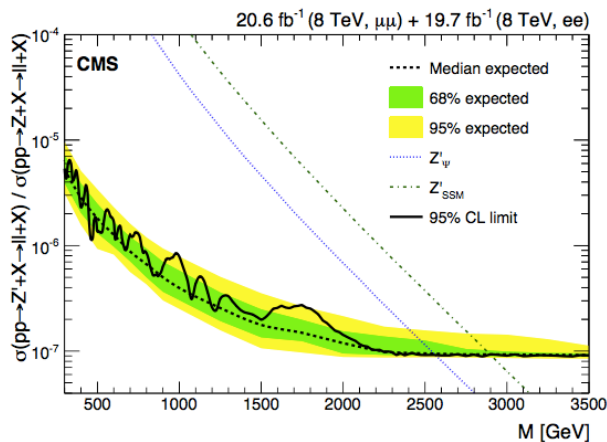




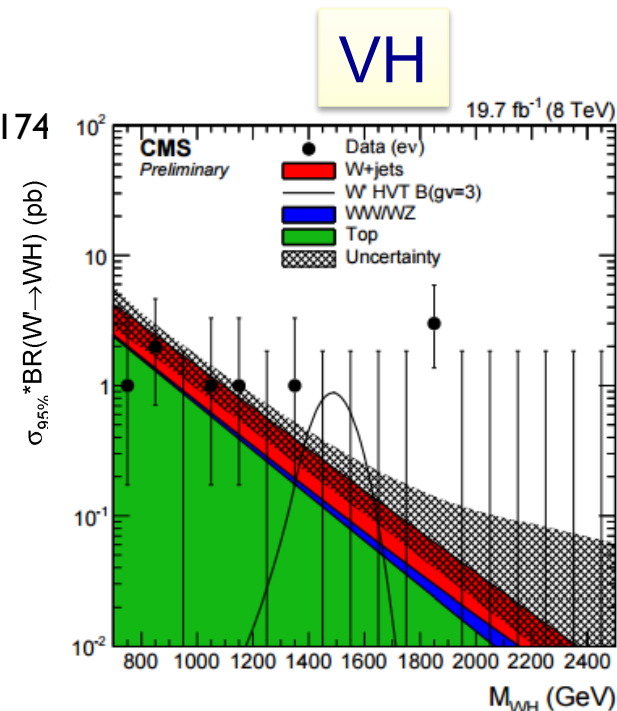
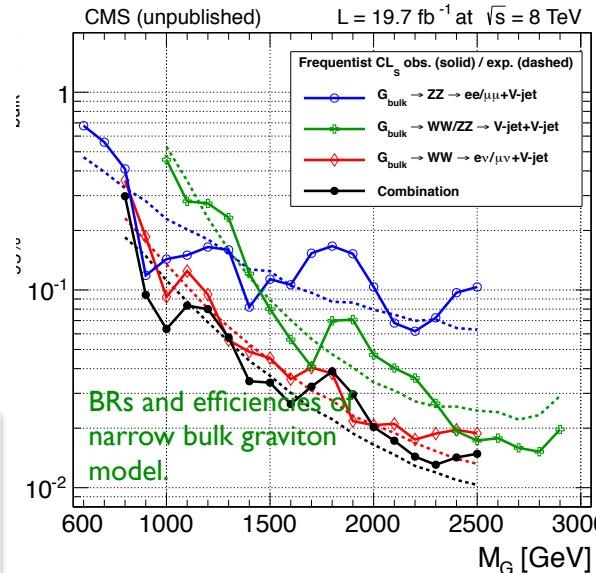
# How will it rear its head?

- Whatever NP is out there, it may well start showing up as a *number* of excesses in several channels (and not as a single  $5\sigma$  signal).

Combination: EXO-13-009  
(includes EXO-12-024)



[http://dx.doi.org/10.1007/JHEP08\(2014\)174](http://dx.doi.org/10.1007/JHEP08(2014)174)



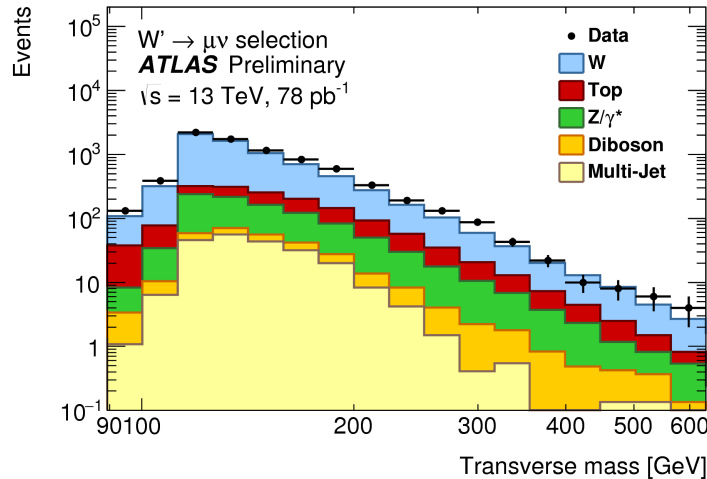
**Disclaimer: this transp for illustration only; NOT a claim of NP.**

And there will be inconsistencies...  
LEE in theory/model space?

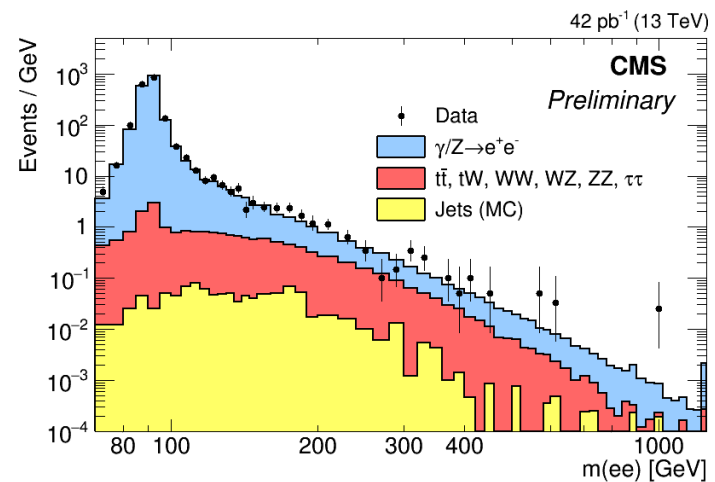
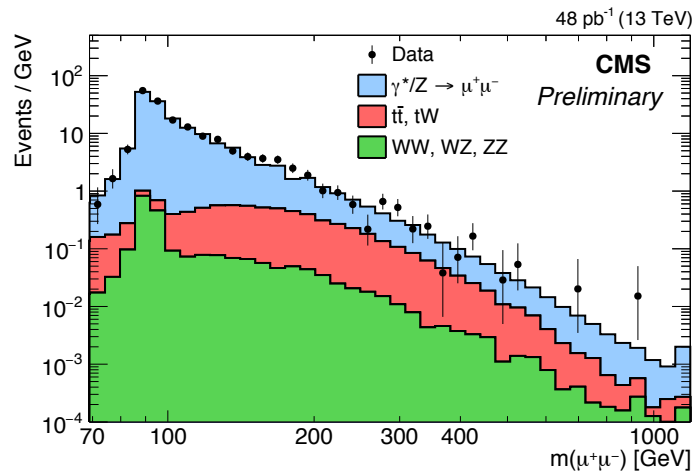
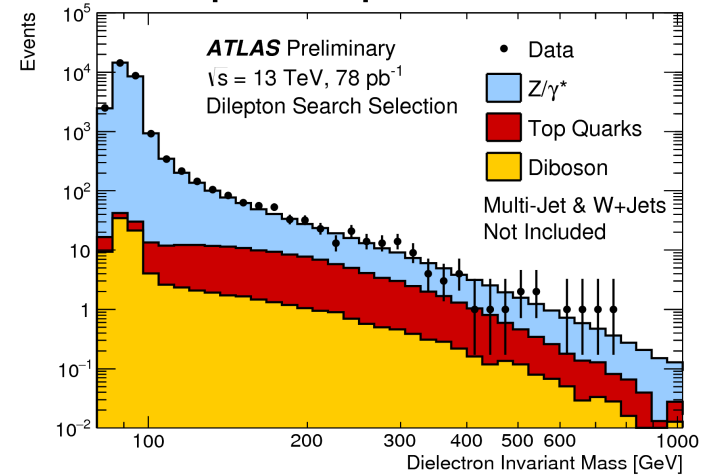


# W', Z': Early look at 13 TeV

lepton+MET mass (W')



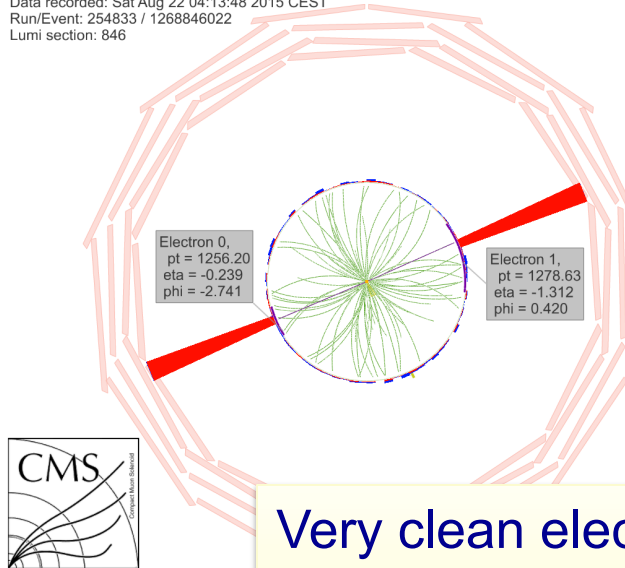
di-lepton spectrum



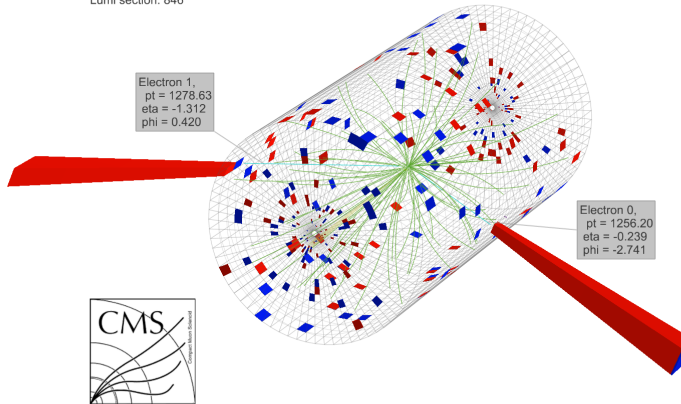
And just as people were packing to come to St. Petersburg...

# An ee event with mass 2.9 TeV...

CMS Experiment at LHC, CERN  
Data recorded: Sat Aug 22 04:13:48 2015 CEST  
Run/Event: 254833 / 1268846022  
Lumi section: 846



CMS Experiment at LHC, CERN  
Data recorded: Sat Aug 22 04:13:48 2015 CEST  
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Lumi section: 846

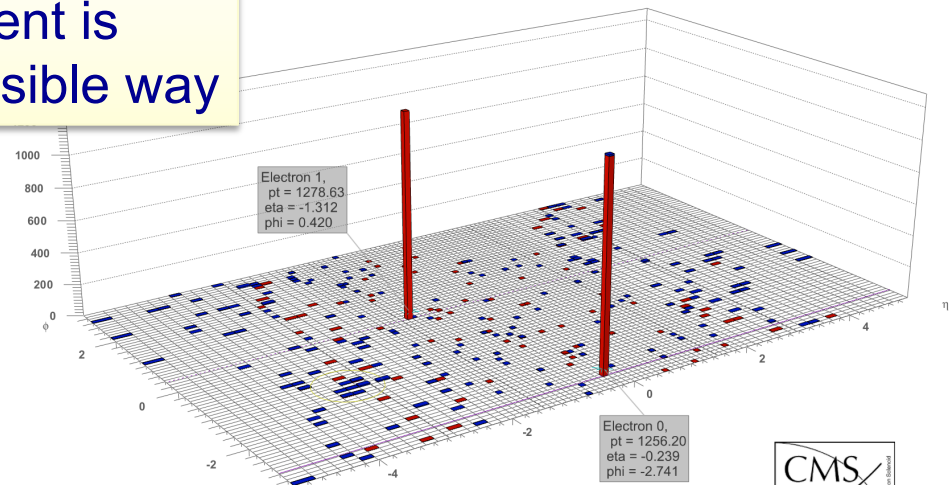


**VERY preliminary**

mass range	SM Bkg Expection
>1 TeV	0.21
> 2 TeV	0.0067
> 2.5 TeV	0.0017

Very clean electrons; event is spectacular in every possible way

	electron 0	electron 1
$E_T$	1260 GeV	1280 GeV
$\eta$	-0.24	-1.31
$\phi$	-2.74 rad	0.42 rad
charge	-1	+1
mass	2.91 TeV	
$\cos \theta^*_{CS}$	-0.49	
$y$	0.78	

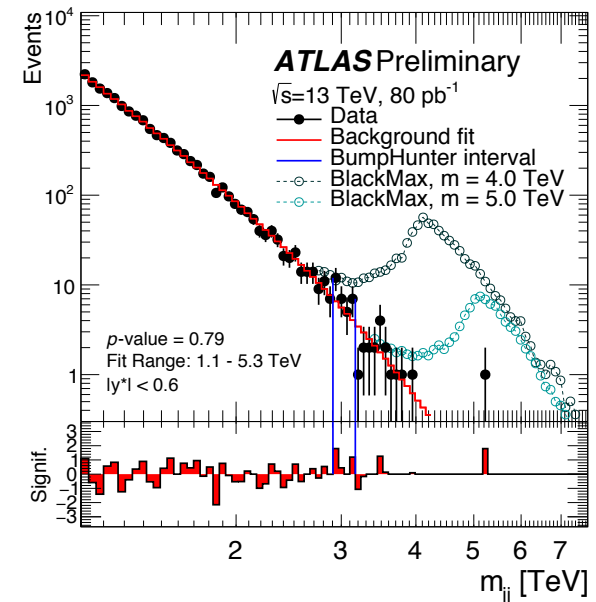
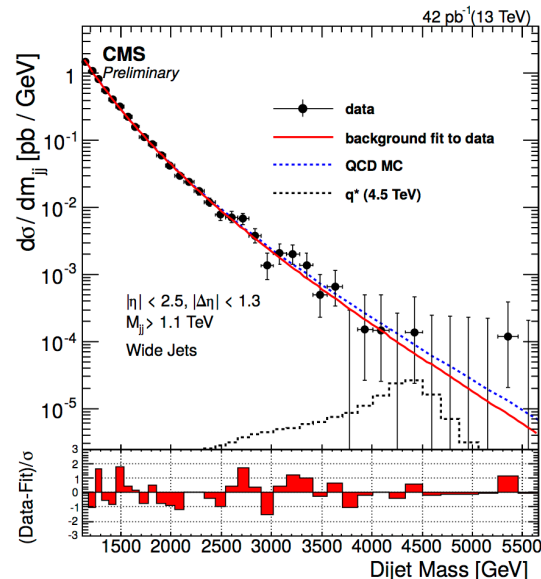
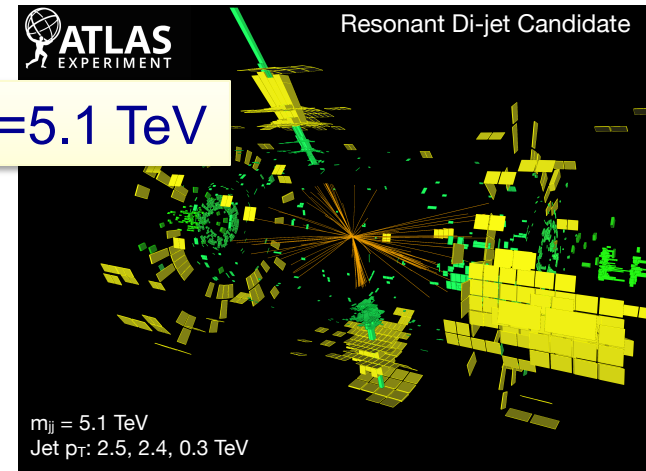
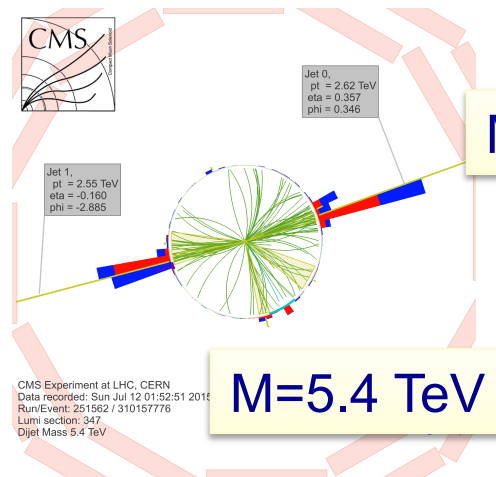


CMS Experiment at LHC, CERN  
Data recorded: Sat Aug 22 04:13:48 2015 CEST  
Run/Event: 254833 / 1268846022  
Lumi section: 846

# Jet Resonances (?)

- Dijets and di-electron events...
- Looks like 2015 will be the year of event counting...

Two distributions to watch



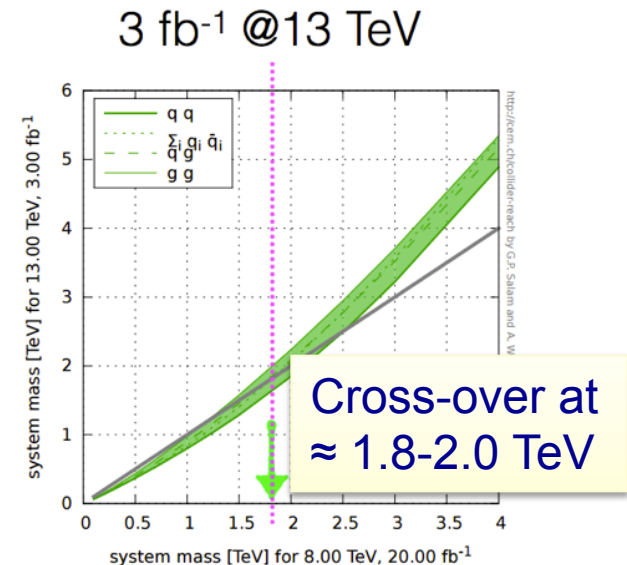
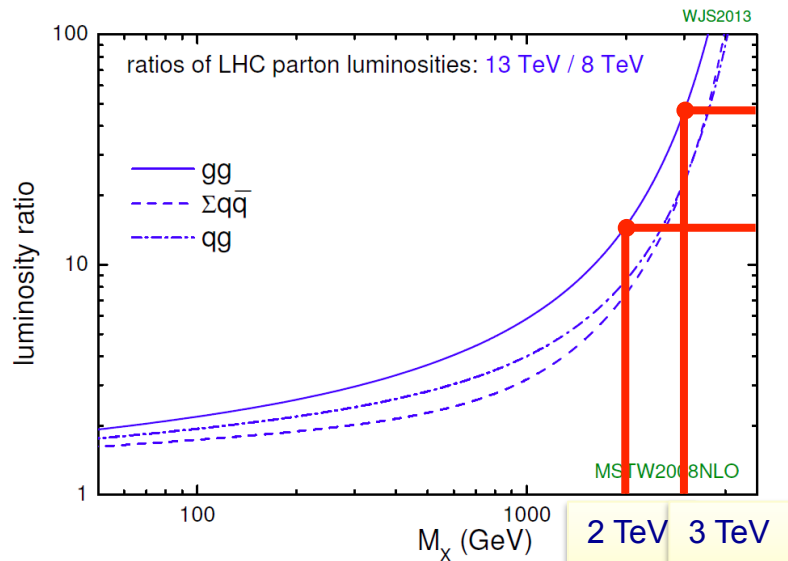
**And now what?**

**Great Expectations**

# Run II has started; Run II is on

- We'll soon be crossing the “few fb<sup>-1</sup> at 13 TeV” mark

	Peak lumi E34 cm <sup>-2</sup> s <sup>-1</sup>	Days proton physics	Approx. int lumi [fb <sup>-1</sup> ]
2015	~0.5	65	3
2016	1.2	160	30
2017	1.5	160	36
2018	1.5	160	36



# What we have learned from the LHC: summary (so far)

- **Standard Model: a VEFT [Very Effective Field Theory]**
  - ◆ Our understanding of the strong and electroweak interactions has improved dramatically.
    - Amazing NLO and NNLO calculations that describe the data!
  - ◆ Heavy ions: new understanding of “surroundings”
- **A fundamental scalar that couples to mass. At 125! ???**
  - ◆ Huge literature (and litterature) on the 125.
  - ◆ A very large set of questions now on the frontline.
- **Amazingly, no new physics has been discovered (yet)**
  - ◆ Supersymmetry is ever elusive; Exotica are, for now, just that; Nothing new in the flavor sector either.
- **“Only” one new boson, yet so many new questions:**
  - ◆ Is it the very Higgs of the SM? Elementary or Composite? First scalar of many? Is it “natural”? Does it couple to Dark Matter? Connection to matter-antimatter asymmetry? ...
- **The good news: we will get answers to some of these questions soon (LHC Run II and beyond)**